Investigation of nutrient management trade-offs using the Land Utilisation Capability Indicator (LUCI).

A Canterbury, New Zealand, case study

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Gowera Grace Tariro

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Although agricultural productivity aims to meet global food demand, its expansion and intensification has led to an increase of nutrient load in water ways affecting water quality. This places farmers under pressure in controlling nutrient loss and conserving ecosystem services. The Land Utilisation Capability Indicator (LUCI) model can assist farmers in meeting freshwater policy requirements and identifying where changes on current land management can be done. LUCI is an ecosystem service modelling tool which illustrates the impacts of various ecosystem services. The model was applied in the Selwyn catchment to identify trade-offs between agricultural productivity and water quality. Trade-off results highlighted possibilities of improving water quality at the expense of agricultural productivity. However, to minimise loss of agricultural land or productivity, LUCI identified specific positions within the catchment which require nutrient mitigation. The study also modified the LUCI model. Without any alterations, LUCI uses soil type to determine nutrient loads in a catchment. Modifications done enabled land use to determine nutrient loads. The modifications included adding the Selwyn catchment farm data into the Land Cover Database (LCDB4), assigning export co-efficient (EC) values to different farm types in the study area. LUCI uses the export coefficient approach to calculate nutrient load of an area. Results from the modification process identified dairy farmers as major contributors of nutrient load.

Keywords: Agricultural productivity, water quality, LUCI, trade-offs

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Table of Contents

List of figures

List of tables

List of appendices

List of abbreviations

SWAT-CUP	Soil and Water Assessment Tool- Calibration or Uncertainty Program
CLUES	Catchment and Land use for Environmental Sustainability
InVEST	Integrated Valuation of Ecosystem Services Trade-offs
ARIES	Artificial Intelligence for Ecosystem Services
LUCI	Land Utilisation Capability Indicator
MEA	Millennium Ecosystem Assessment
SWAT	Soil and Water Assessment Tool
GIS	Geographic Information System
RMA	Resource Management Act
DEM	Digital Elevation Model
EC	Export Coefficient
ES	Ecosystem Services
TP	Total Phosphorus
TN	Total Nitrogen

CHAPTER 1: INTRODUCTION

1.0 Introduction

Impacts of agriculture on water quality have been a subject of research since the 1960s. A considerable amount of literature has been published on this topic, and results have identified nutrient pollution as one of the major effects. While expansion and intensification of agriculture have increased to meet the global food demand (Tilman, Balzer, Hill, & Befort, 2011), other aspects of the environment have deteriorated. Reports and studies reveal that agricultural intensification alters the environment in several ways such as accelerating soil erosion, changing wildlife habitats and polluting water bodies (Scanlon, Jolly, Sophocleous, & Zhang, 2007; Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005).

In New Zealand, water pollution is a major environmental issue and measures are being taken to reduce its severity and maintain New Zealand's clean, green image. Whilst point sources have been reduced, diffuse pollution is the primary source of water contamination and the development of strategies to control it is still being implemented (Environment Foundation, 2018b).

Agriculture plays an essential role in New Zealand's economy, contributing approximately 5% of the country's Gross Domestic Product (GDP) (Environment Foundation, 2018a). However, agriculture provides much of the pressure on New Zealand's freshwater, and the role of agriculture has received increasing public attention in the past decade (Environment Foundation, 2018a). In recent years, concerns have been raised about the effect of intensification of dairy farming on water quality and the Dairying and Clean Streams Accord was established to address problems with water pollution due to dairy farming (Fonterra, 2004).

To meet the demand for water quality management, several modelling tools have been developed, and these range from tools that provide a simple mapping of ecosystem services to advanced process-based models as suggested in Jackson et al. (2013). Addressing water quality issues through the idea of ecosystem services provides a more holistic understanding of the causes and wider effects of water quality deterioration.

According to the Millennium Ecosystem Service (Millenium Ecosystem Assessment, 2005), ecosystem services (provisioning, regulating, supporting and cultural), are the benefits people obtain from ecosystems such as food, habitat provision, recreational, and water purification. The Millennium Ecosystem Assessment was published in 2005 and has been used worldwide as a framework for understanding and assessing ecosystem services. The objective of this assessment was to evaluate the effects of altering the ecosystem for human well-being and findings revealed that ecosystems have deteriorated rapidly and extensively over the past 50 years resulting in irreversible loss of diversity of life on earth.

Models that incorporate ecosystem services can be used to assist in land management decision making. Amongst these tools, the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) and Artificial Intelligence for Ecosystem Services (ARIES) are the most popular. InVEST is a suite of free, open-source software models used to map and value the goods and services from nature that sustain and fulfil human life (Ouyang et al., 2016). ARIES is a networked software technology that redefines ecosystem service assessment and valuation for decision making (Villa, Ceroni, Bagstad, Johnson, & Krivov, 2009). The Land Utilisation Capability Indicator (LUCI) is a recent addition to existing tools and is the focus of this research.

1.1 General description of LUCI

LUCI is an ecosystem service modelling tool that displays the impacts of land-use on various ecosystem services (Jackson et al., 2013). Previous research by Bagstad, Semmens, Waage, and Winthrop (2013) indicates that out of the 17 ecosystem service tools used in a comparative assessment, LUCI was the only tool capable of both site and landscape-scale modelling.

LUCI is a Geographic Information System (GIS) based framework, which currently houses seven single ecosystem service sub-models (water quality, carbon sequestration, agricultural productivity, erosion risk and sediment delivery, habitat provision, and flood mitigation). Mass transport in LUCI is driven by unique hydrological routing algorithms, which operate at an underlying digital elevation model (DEM) scale, allowing modelling of the entire ranges of scale to co-occur.

Individual ecosystem services can be evaluated, and interrelationships between these ecosystem services can be assessed to identify trade-offs between them. LUCI uses readily available national data and the minimum data requirements are a digital elevation model (DEM), soil type, land cover, evapotranspiration, and rainfall. LUCI generates several maps and data to summarise generated results of each analysis and allow exploration of total nitrogen (TN) loads, total phosphorus (TP) loads and agricultural utilization in-stream and on land (Jackson et al., 2013).

The Soil and Water Assessment Tool (SWAT) will be used to compare against LUCI to explore the similarities and differences of both models. The SWAT model was chosen amongst several water quality models because it can be used to quantify ecosystem services and it is applicable in New Zealand. The model is catchment-based and is used to predict the impact of land management on water, sediment, and nutrients. The input data requirements for SWAT include the topography, soil and land use (Arnold et al., 2012).

This research used LUCI to identify the nutrient (nitrogen and phosphorus) and agricultural status as well as trade-offs within the Selwyn catchment in New Zealand's South Island and to identify options to reduce nutrient inputs to the river. The Kaituna catchment, a smaller catchment to the Selwyn, was used as a pilot study to familiarise with the model and achieve the same objectives for Selwyn catchment.

1.2 The Kaituna catchment

The Kaituna catchment is located on Banks Peninsula, South Island in New Zealand. The basin is characterized by volcanic geology with soils rich in phosphorus. The catchment comprises the Kaituna valley which is characterised by steep slopes. The Kaituna catchment is approximately 4900 ha long and feeds directly into Te Waihora. It is very important for *Ngāi Tahu* particularly for the *Koukourārata* hapu of Banks Peninsula who used the Kaituna Valley as their traditional pathway to Te Waihora, Canterbury's largest lake, to gather *Mahinga kai* (Te Runanga o Ngāi Tahu, 2015). Previous researches done by ECan indicated that between

2004 and 2005, faecal contamination had elevated greatly above the required water standards whilst the other pollutants (nutrients and sediments) had increased too. Reports also indicate that high faecal contamination was due to direct access of cattle to waterways (Waihora Ellesmere Trust, 2016).

1.3 The Selwyn catchment

The Selwyn catchment, located in the Selwyn district, South Island in New Zealand. The headwaters of the Selwyn River are in the foothills of the Southern Alps of the South Island of New Zealand (Jenkins, 2017). The river crosses the alluvial Central Plains of the Canterbury region and discharges into Lake Ellesmere/Te Waihora. In the upper reaches the river loses surface water to the groundwater system while in the lower reaches when the groundwater table reaches the elevation of the riverbed the river gains flow from groundwater (Jenkins, 2017).

Lake Ellesmere/Te Waihora is a brackish coastal lagoon and is New Zealand’s fifth-largest lake by area. The lake provides a wetland habitat for an extensive range of birds, invertebrates and plant species and is used for commercial and recreational purposes. It is of cultural importance to the *Ngāi Tahu* as a major *mahinga kai* site and an essential source for mana. Nationally and internationally, the lake is significantly known for its wildlife importance. A diverse range of exotic and indigenous fish such as trout, shortfin eel, salmon, and inanga are supported by the lake (Kitto, 2010). The lake has been in a hypertrophic state for the past eighteen years making it unsuitable for recreational activities due to excessive nutrients and high turbidity (Selwyn-Waihora Zone Committee, 2018).

Influenced by accelerated agricultural activities, the Selwyn district is one of the fastest-growing locations in New Zealand. Agriculture contributes 30% of the district's economic success but has led to a decrease in water quantity and with high nitrogen concentrations in shallow groundwaters and lowland streams (Selwyn District Council, 2018). Previous researches have indicated that 95% of the total nitrogen loads in the Selwyn catchment have been contributed by losses from agriculture and that an estimate of 3,200 t/yr. of nitrogen load reaches Te Waihora (CWMS, 2005).

To control water quality within Canterbury, the Resource Management Act (RMA) has been used as a legislative framework. However, because the RMA was designed when water availability was abundant, continual reliance on the act on sustainability was inadequate because of irrigation expansion in Canterbury. This led to a change in water management which incorporated issues such as water allocation and availability and management of cumulative effects of land-use intensification. This gave rise to the development of the Canterbury Water Management Strategy which is responsible for managing the region's water resources. The strategy uses the collaborative governance concepts and Zone Committees have been established to recommend zone implementation programs for the strategy (Jenkins, 2018).

Considering that agricultural activities within the catchment may not decrease but instead increase due to the economic value in return, water quality will continue to deteriorate unless efficient and sustainable practices are put into place. Although polices and regulations set within the catchment are being used, nutrient losses have not decreased though change may take time to notice. Therefore, there is a need for researchers to come up with measures that enable agriculture to occur with the minimum release of nutrients in waterways.

1.4 Aims and Objectives

This aim of the thesis is to assist in improving water quality by exploring how easy the Land Utilisation Capability Indicator (LUCI) could be implemented in the Selwyn catchment as a GIS modelling tool. This includes examining trade-offs between agriculture and water quality (primarily the nutrients nitrogen and phosphorus) with the model's built in tools. The research will identify positions within the catchment that require management intervention to improve water quality.

The objectives to achieve the aim stated above are:

1. **Identifying sources of nitrogen and phosphorus.**

   Water quality tools within LUCI will be used to identify sources of both nitrogen and phosphorus.

2. **Assessing agricultural utilization status of the study area.**

   The Agricultural Productivity tool within LUCI will be used to achieve this objective. This will look at the current and predicted agricultural activities within the catchment and will identify positions where land is over and underutilized for agricultural purposes. Lastly, the tool will be used to consider whether current agricultural utilization is worthy of preservation or change.

3. **Investigating trade-offs between agricultural production and water quality in the study area.**
   Trade-offs are defined as opportunities that exist to improve service delivery. In this case, the trade-off tool will be used to identify positions within the catchment where agriculture can take place with minimum nutrient loss when there is management intervention.

1.5 Thesis structure

This thesis comprises five primary chapters.

1. Chapter 1

Introduces the research topic and outlines the aims and objectives of the thesis. Section 1 also gives a brief overview of LUCI.

2. Chapter 2

Defines and describes the ecosystem service concept, provides an overview of agriculture and freshwater in New Zealand, discusses the impacts of agriculture on water quality, and provides a description of water quality models and a detailed explanation of the LUCI model. This chapter will also give a comparison between the LUCI and SWAT models.

3. Chapter 3

The third chapter is concerned with the methodology used for this study. A brief introduction of the two case studies used is given as well as outlining the data used for the research. The

LUCI modelling process will be discussed and lastly, the steps taken to modify the model will be described.

4. Chapter 4

This section presents the findings of the research, focusing on the first three objectives of the study in both catchments. The results chapter will outline results generated before and after the model was modified.

5.Chapter 5

This chapter concludes the thesis, discusses the findings, provides recommendations and gives the thesis conclusion.

CHAPTER 2:LITERATURE REVIEW

2.0 Chapter summary

LUCI falls under the ecosystem services models therefore, the literature review will give a brief outline of the development of ecosystem services and will discuss the Millennium Ecosystem Assessment, an assessment that popularised the Ecosystem service subject and has been used as a framework for understanding and assessing ecosystem services. This research looks at the impacts of agriculture on water quality, hence an overview of these impacts will be discussed as well as ways of controlling the impacts. To understand how nutrient export is managed from agricultural systems in New Zealand, this chapter will give a highlight of policies and regulations used. Water quality models applicable to New Zealand for decision-making in water quality control are discussed and lastly a detailed explanation of how the LUCI model functions are given. Lastly, a comparison between the LUCI and SWAT models will be given.

2.1 Defining Ecosystem Services

The concept of ecosystem services has become an important area of investigation over the past decade due to its link between the functioning of ecosystems and human welfare (Fisher, Turner, & Morling, 2009). An understanding of this link is crucial for decision-making. This concept emerged in the 1970s as environmental science (de Groot, 1987; Wilson & Matthews, 1970) and was later renamed to ecosystem services in the mid-1980s (Ehrlich & Mooney, 1983). In the 1990s, interest in methods to estimate ecosystem services' economic value increased (Costanza et al., 1997) and the concept continued to gain momentum from 1997 onwards.

The Millennium Ecosystem Assessment (MA), popularised the ecosystem services concept through their assessment, which was initiated in 2001. The program was designed to meet the needs of the public and decision-makers concerning the consequences of ecosystem change for human well-being (Board, 2005; Millennium Ecosystem Assessment, 2003). It involved 1, 360 experts from 95 countries and was conducted at local, watershed, national, regional and global scales (Carpenter et al., 2009). The main findings of the MA indicated that ecosystems have been rapidly and extensively altered by humans over the past 50 years resulting in irreversible loss of diversity of life on earth (Norgaard, 2008).

Benefits from ecosystems, such as food, freshwater, and wood, are known as ecosystem services. The term ecosystem services have been defined differently by several authors and according to Fisher et al. (2009), the three most widely cited definitions are:

- The conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life (G. C. Daily, 1997).
- The benefits human populations derive, directly or indirectly, from ecosystem functions (Costanza et al., 1997).
- the benefits people obtain from ecosystems (Millenium Ecosystem Assessment, 2005)

The Millenium Ecosystem Assessment (2005) grouped ecosystem services into four broad categories (Fig 1) namely:

- Provisioning services are products obtained from the ecosystem such as food, water, fuel, wood, and fibre;

- Supporting services enable ecosystems to continue rendering all other ecosystem services and examples of these include, nutrient cycling, soil formation, primary production and, habitat provision;
- Regulating services are benefits obtained from the regulation of ecosystem processes and these include water purification, climate and flood regulation;
- Cultural services are non-material benefits obtained from the ecosystem such as spiritual, aesthetic, educational, and recreational (Alcamo, 2003).

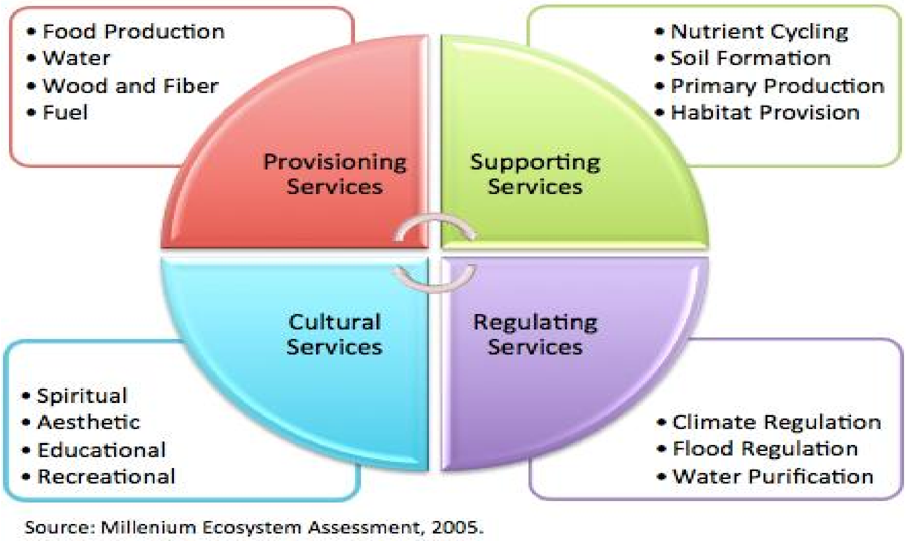

Figure 1: Categories of ecosystem services (Millenium Ecosystem Assessment, 2005)

Ecosystem services are taken for granted because they are available freely. However, their importance becomes much clearer when they start declining (e.g. through water pollution and soil degradation) and when there are conflicting demands on use. They are essential for our survival; we all require healthy ecosystems so that we have clean air to breathe and freshwater to drink and as populations increase dependence on healthy ecosystems also increases. Therefore, there is a need to understand more about ecosystem services to conserve and protect them.

2.2 Agriculture and water quality in New Zealand

Agriculture plays an essential role in New Zealand's economy, contributing approximately 5% of the country's Gross Domestic Product (GDP) (Environment Foundation, 2018a). The dairy industry has increased significantly in the entire New Zealand as shown in Fig 2. In Canterbury, as from 2012 to 2017, there has been a 9% growth in the dairy industry which was facilitated by an increase of 8% in the irrigation sector (Stats NZ, 2017). Though this implies significant economic growth in the province, the increase in dairy farming is also associated with higher inputs of fertilizer and feeds which are linked to the release of high quantities of animal excreta deposited into the fields. This excreta is a primary source of both nutrients and faecal bacteria that concentrate on waterways through leaching and runoff (Monaghan et al., 2007). The rapid growth of urbanization and agriculture is contributing to water pollution (Ballantine & Davies-Colley, 2014), which places non-point source pollution on the top list of major contributors of water contamination (Davies-Colley, 2013).

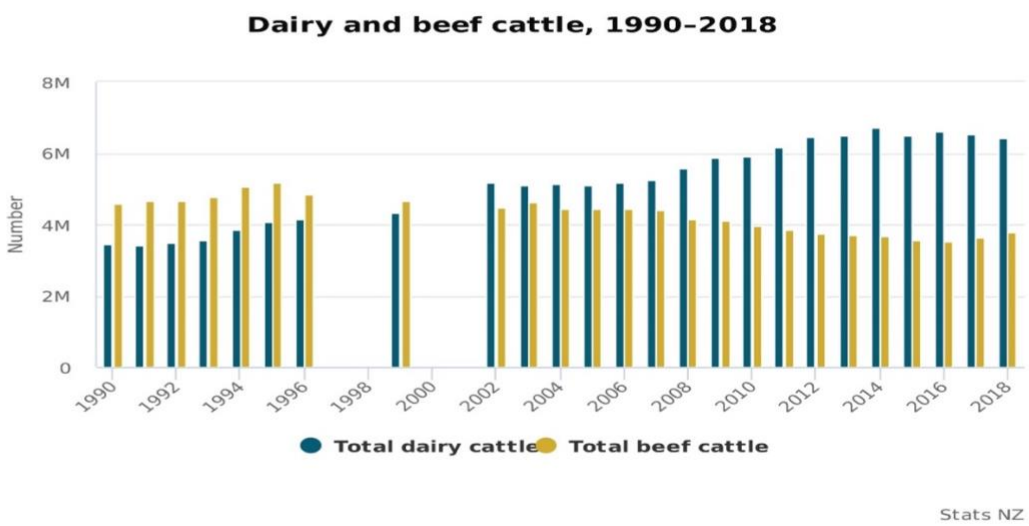

Figure 2: Dairy and beef cattle growth trends (Stats NZ)

Although New Zealand has an ongoing overall ready availability of freshwater which varies considerably by area, increased pressures on water resources have become an issue of concern on the state of water quality across the country (Cullen, Hughey, & Kerr, 2006). Water quality refers to fitness for intended use which is determined by the physical, chemical and biological parameters of water. Although some rivers in New Zealand are polluted, river water quality compared to Europe, Asia, and North America can be regarded as fairly good (Davies-Colley, 2013).

To determine the health status of lakes in New Zealand, the trophic level index (TLI) is used; the higher the TLI number, the poorer the water quality. TLI is calculated using the total nitrogen, total phosphorus, water clarity, and chlorophyll then combines these parameters into one number. Table 1 below (LAWA, 2015), shows the different categories of nutrient enrichment with their corresponding values.

Table 1: Trophic Level Index (LAWA, 2015)

Index	Description	LAWA Icon
Less than 2	Microtrophic: The lake is clear and blue with very low levels of low levels of nutrients and algae.	VERY GOOD
2-3	Ogliotrophic: The lake is clear and blue, with low levels of nutrients and algae	GOOD
3-4	Mesotrophic: The lake has moderate levels of nutrients and algae.	AVERAGE
4-5	Eutrophic: The lake is green and murky, with higher amounts of nutrients and algae.	POOR
Greater than 5	Supertrophic: The lake is fertile and saturated in phosphorus and nitrogen, often associated with poor water clarity.	VERY POOR

The TLI for Lake Ellesmere/Te Waihora has been ranging consistently around seven since 2000 which indicates a hypertrophic level (Fig. 3) (Selwyn-Waihora Zone Committee, 2018). A hyper trophic level shows that the lake has excessive nutrients, high turbidity, unsuitable habitat for fish, and is not fit for recreational use.

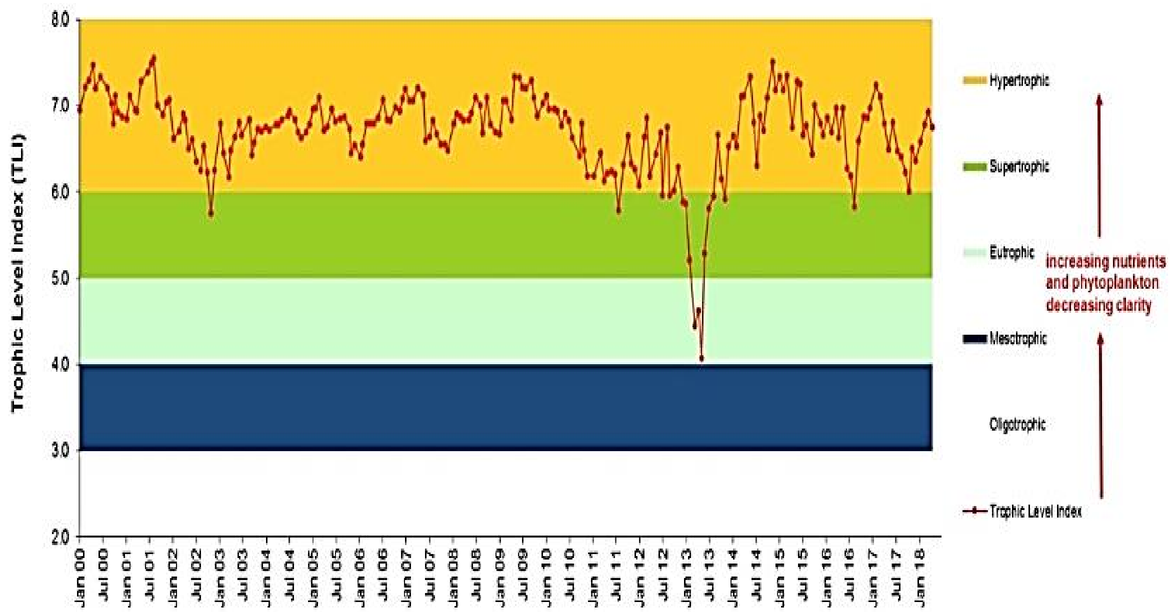

Figure 3: Trophic level index for Lake Ellesmere/ Te Waihora (Selwyn-Waihora Zone Committee, 2018)

2.3 Water quality legislation in New Zealand

The legislation implements and enforces water quality standards in New Zealand. The Resource Management Act 1991 (RMA) is the primary legislative instrument that provides a guide for water resource management (Ministry for Environment, 2018). It uses the first come first served principle to allocate water and decision-making is decentralized, which gives power to regional councils to establish plans and policy statements to develop criteria for water management (Kaye-Blake, Schilling, Nixon, & Destremau, 2014). Under the RMA, discharges into waterways (diffuse and point source) require a resource consent unless they fall under the permitted category of the regional plan. A resource consent is an official authorization given to activities that do not meet the requirements of a regional plan (Ministry for Environment, n.d). The government provides national direction for water through instruments such as the national policy statement.

The National Policy Statement for Freshwater Management (NPS-FM) provides the main national direction which guides the local government on how they should carry out their responsibilities when managing freshwater under the RMA principles. The regional councils, after consulting their communities, layout objectives for the state of water bodies in their region and set limits on resource use to achieve the set objectives (Ministry for the Environment, 2018).

2.4 Impacts of agriculture on water quality

The agricultural sector is by far the biggest user of freshwater and It is estimated that 85-90% of all freshwater is used for agricultural purposes in Africa and Asia (FAO, 2017). In New Zealand, agriculture uses more than half of the water supply (Parliament NZ, 2010). Pollutants enter waterways through point or non-point sources. Point sources are easy to identify and hence makes it easier to control contamination. Non-point source pollution comes from various sources such as agricultural activity, urban runoff, and construction sites therefore, making it difficult to control (National Research Council, 2000).

While agriculture is not the only activity with the potential to affect freshwater negatively, it is a crucial one. In New Zealand, the major contaminants of water are nutrients (nitrogen and phosphorus), sediments, and bacterial contamination (Parliamentary Commissioner for the Environment, 2013).

2.4.1 Nutrients

When nutrients from fertilizers or animal waste enter waterways, they speed up eutrophication. Eutrophication is the excessive richness of nutrients in water bodies caused by runoff from the land leading to the dense growth of plant life (Dodds & Smith, 2016). Fertilizers and animal waste contain nitrogen and phosphorus, which affect water quality when in excess. Nitrogen is a major component of chlorophyll, which is required by plants to produce their food through the process of photosynthesis (Fageria, 2016). It enters waterways either in chemical or dissolved forms. It is very soluble hence it can enter waterways very easily through leaching into groundwater or via overland flow. Drinking water rich in nitrates causes a blue-baby syndrome in infants (methemoglobinemia). This condition affects the amount of haemoglobin in the blood and is characterized by blue skin colour. The condition can be treated (Majumdar, 2003). Phosphorus is essential for plant growth and naturally occurs in soils. It occurs in dissolved organic or inorganic form or can be attached to sediment particles. The main way it gets into water is through erosion of sediments.

Excessive amounts of nutrients trigger growth of unwanted plants in water such as algae, and, choking weeds (Parliamentary Commissioner for the Environment, 2013). When algae die, they decompose and, in the process use up oxygen, making it difficult for other organisms to survive. Unwanted plants may reduce the aesthetic value of lakes, affect recreational activities and produce an unpleasant odour. These unwanted plants can be grouped into four categories periphyton, macrophytes, phytoplankton, and cyanobacteria. Periphyton (Fig. 4) is the slime coating objects in streams. It coats submerged objects in either green or brown (Biggs, 2000) and grows in shallow water. Macrophytes are plants that grow in or near water. They may be emergent, submerged or floating on water, examples of these include the eelgrass and hornwort. They grow deep into the water, develop roots in the sediments and reach up for sunlight. Phytoplankton and cyanobacteria form mats, which can cover a large area when they bloom. Phytoplankton floats in the water. It is composed of tiny plants that multiply exceptionally rapidly, particularly in summer, covering large water surfaces with bright green algal blooms (Parliamentary Commissioner for the Environment, 2013). Cyanobacteria is often called blue-green algae, although it is not actually algae nor is it usually blue-green, but can be many colours such as dark brown or red. In lakes cyanobacteria generally float; in rivers, they form part of the periphyton covering stones on the bottom (Parliamentary Commissioner for the Environment, 2013).

Figure 4: Periphyton growth in Freshwater (Ewart-Smith J, Graham M, Pillay P, & Singh S, 2017)

2.4.2 Erosion and sedimentation

Sedimentation in streams is a natural process and the geology of the surrounding area determines the type and amount of deposits in the water. Soil erosion transports sediments into water bodies, and erosion accelerates in regions of high topography and low vegetation cover. Human activities such as land clearing for land-use change has a significant impact on the rate of erosion. Sedimentation tends to be lower under mature indigenous forest cover and increases significantly when the forest is cleared and replaced with pastures (Davis, Pearson, Brodie, & Butler, 2017).

Excessive amounts of sediments have a negative impact on water quality and quantity. They reduce water clarity and decrease visibility. Water clarity affects light penetration, which in turn affects the growth of aquatic plants, which are a source of food to aquatic organisms. When visibility is reduced, it affects organisms in food hunting. Sediments can also affect benthic habitat and recreational activities such as fishing and swimming since each activity has a required threshold value. The ANZECC guidelines for fresh and marine water advise that rivers with a low clarity of less than 70 cm should be protected to safe keep aquatic life and for human recreation, 1.6 m clarity is required (ANZECC, 2000). Clarity is measured by lowering a black and white secchi disk, 20 cm in diameter, attached to either a rod, PVC pipe, rope or chain and recorded at what depth is ceases being visible (Noble Research Institute, 2002).

2.4.3 Bacteria

The main sources of pathogens in freshwater are human and animal excreta. In New Zealand, human excreta is treated by municipal sewage treatment plants before being discharged into the water to reduce the number of pathogens (Parliamentary Commisioner for the Environment, 2013). With animals, some of their waste are deposited directly into water and some is washed away into waterways from farms. This waste material contains pathogens such as E. coli which can be harmful to humans.

E. coli is a type of faecal coliform bacteria that is found in the intestines of animals. The bacterium is deposited into the environment through the deposition of faecal material and is used as an indicator host. Its presence in water bodies signifies contamination from sewage or animal waste. In humans, E. coli may result in skin irritations, eye infection and gastrointestinal illness (Al-Badaii & Shuhaimi-Othman, 2015).

2.5 Protecting and improving water quality

Several ways can be employed to control water quality although some may not be effective enough to notice the change. Most of the methods require continuous management to enable effective control. The most popular general methods include riparian planting, wetlands, and timing and split fertiliser applications. In addition to the methods, the duration controlled grazing system can be used. With this system, cows are given a short period to graze on pasture (four hours) before they are moved to a stand-off facility for excretion and rumination. Animal waste is collected from the stand-off facility, reducing the amount of animal waste which could be transported into waterways (Christensen, Hedley, Hanly, & Horne, 2012).

2.6 Water quality modelling

Water quality modelling involves the prediction of water pollution using mathematical simulation. These models are extensively used in research and have been constantly updated and refined to meet new and emerging problems of surface water such as eutrophication (Rauch et al., 1998). However, despite the efforts of researchers and the government to control water pollution, water quality continues to deteriorate.

The process of determining sources and the amount of contamination in waterways is complex (S. Anastasiadis et al., 2013; Tsakiris & Alexakis, 2012). This complexity arises as a result of spatial variability in topography, soil, land use, temporal variability of climate and management practices (S. Anastasiadis et al., 2013). Since direct measurement of sources of pollution is not always feasible, scientists and researchers have developed water quality models to assist in interpreting water quality patterns (Anastasiadis et al., 2013). Water quality models provide a more physically-based representation of the processes that contaminate water. They can be used to evaluate scenarios such as estimating and predicting levels of pollution in water bodies (Wang, Li, Jia, Qi, & Ding, 2013), and predicting the impact of different management strategies (Snelder & Hughey, 2005)

Models address different problems and work under different scenarios; therefore, according to Tsakiris & Alexakis, (2012) they are classified into different categories according to:

- Type of approach (physically-based, conceptual, or empirically based)
- Pollutant item (nutrients, sediments)
- Area of approach (catchment, groundwater, river system)
- Nature of application (deterministic, stochastic)

- State analysed (steady-state or dynamic simulation)
- Spatial analysis (lumped or distributed)
- Dimensions (1-D or 2-D models)
- Data requirements (extensive databases, minimum requirement models) (Tsakiris & Alexakis, 2012)

2.6.1 Water quality models used in New Zealand

A wide range of water quality models has been applied in New Zealand to assist in solving water quality issues. These models range from farm-scale nutrient models (Overseer and SPASMO) to catchment scale models (SWAT, CLUES). They provide information on the impacts of different land-use on water quality and can estimate the amount of nutrients lost into waterways.

2.6.1.1 Catchment and Land Use for Environmental Sustainability (CLUES)

CLUES is a popular catchment-based model developed by the National Institute of Water and Atmospheric Research (NIWA) for the Ministry of Agriculture and Forestry (MAF). The model is GIS-based and predicts estimates of nutrients, E.coli, sediment loads and concentrations at catchment, regional and national levels (S. Anastasiadis et al., 2013; S. Elliott, Semadeni-Davies, & Shankar, 2011). CLUES utilises three water quality models: OVERSEER, Soil and Plant Atmosphere System Model (SPASMO) and Spatial Regional Regression on Watersheds Attributes (SPARROW) (A. H. Elliott et al., 2016). The key input requirements include topography, soil, land-use, and climate.

In Lake Clearwater, Canterbury, CLUES was applied to evaluate model performance. This was achieved by comparing generated model output with the estimated loads of the lake. Results indicated satisfactory performance for Total Nitrogen (TN) loads after calibration of land use data layer whilst Total Phosphorus (TP) loads indicated poor performance (Caruso, O'Sullivan, Faulkner, Sherratt, & Clucas, 2013).

2.6.1.2 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) model was developed by the USDA Agricultural Research Service (ARS) (Arnold, Srinivasan, Muttiah, & Williams, 1998; Neitsch, Arnold, Kiniry, & Williams, 2011). It evolved from various individual models over 30 years period and has been tested for a wide range of regions, conditions, practices and time scales (Gassman, Reyes, Green, & Arnold, 2007).

SWAT is a continuous-time model that operates on a daily step at the basin scale. It uses data on topography, soil and land use to predict the impact of land management on water, sediment and nutrients in large and complex watersheds. It can be used to evaluate the environmental efficiency of the best management practises and alternative policies (Arnold et al., 2012).

During watershed configuration, the watershed may be partitioned into several sub-watersheds that are further divided into Hydrologic Response Units (HRUs). HRUs are portions in the sub-basin that possess similar land use, topography, soil characteristics and management (Abbaspour et al., 2007).

SWAT has been applied in Motueka River watershed to model the impacts of land cover on critical water resources. Motueka is a case study for a large research project on Integrated Catchment Management (ICM). The results of the research indicated a decrease in total annual water yield in some sub-catchments due to changes in water balance associated with an increase in tall woody vegetation (Cao, Bowden, Davie, & Fenemor, 2009).

2.6.1.3 Overseer

Overseer is a farm-scale nutrient management tool, which is widely used in New Zealand by farmers and farm advisors. The tool illustrates nutrient flow within a farm, provides estimates of nutrient leaching and greenhouse emission. It provides nutrient budgets for nitrogen (N), phosphorus (P), potassium (K), sulphur (S) calcium (Ca), sodium (Na), and magnesium (Mg). Farm and block data are used to prepare nutrient budgets. Initially, the model was developed to assist farmers to make more efficient use of nutrients with the aim to boost productivity and profitability. It was then adopted by regional councils and now it is used as a regulatory tool for nutrient losses to improve water quality (Anastasiadis et al., 2013).

2.7 Ecosystem service modelling

To maintain the sustainability of ecosystem benefits, most national policies and some international agreements include objectives to protect ecosystems (James & Helen, 2018). To manage ecosystems, an understanding of ecosystem services and their condition and extent is required as well as the ability to predict the impacts of alternative policy or management decisions on them. Ecosystem service modelling assists in identifying the impacts of various management options and land use on ecosystem services (Sharps et al., 2017). Several ecosystem service tools have been developed to assist decision-makers in understanding their local systems. These models often consist of a set of modelling tools, each representing an ecosystem service.

2.7.1 Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST)

The Natural Capital Project is a collaboration of Stanford University, World Wildlife, and the Nature Conservancy which developed the software InVEST for quantifying ecosystem service values (Daily et al., 2009). The model is open-source software used to map and value goods and services that sustain and fulfil human life. Decision-makers are often involved in the management of multiple uses of natural resources (land and water) and inevitably they must evaluate trade-offs amongst these uses. InVEST's multi-service design provides an effective tool for evaluating trade-offs (Tallis et al., 2011). The tool currently houses eighteen distinct ecosystem service models designed for terrestrial, freshwater, marine, and coastal ecosystem (Bagstad et al., 2013).

The model has been applied in the Miyun River in China to determine the effects of land use change on ecosystem services. Land-use change in the catchment was mapped using Landsat^{TM} images from 2000-2009. The InVEST model was used to quantify water yield and water purification for good water quality under different land-use scenarios. Results indicated that between the period of 2000 and 2009, forest cover and urban area increased by 33% and 280%, whilst water provision and water purification services declined by 9% and 27% respectively. Under the hybrid scenario where agriculture expanded with riparian grassland buffers, water provision, purification and sediment retention improved (Zheng et al., 2016).

2.7.2 Artificial Intelligence for Ecosystem Services (ARIES)

ARIES is an open-source networked collaborative software technology designed for rapid ecosystem service assessment and valuation. It uses artificial intelligence to couple ecosystem service models with input data to quantify flows for the study area. It was developed as an online platform that allows researchers to contribute scientific data and models that simulate and integrate environmental and socioeconomic systems (Villa et al., 2014). The model can be used on various spatial scales; local, landscape, regional, national and multiscale. It uses spreadsheets, databases (e.g. Access) and maps as input data and it produces maps, quantitative data and environmental asset portfolios as output data. The model focuses on provisioning, regulatory and cultural ecosystem services (Villa et al., 2009).

2.7.3 Land Utilisation Capability Indicator (LUCI)

LUCI is an extension of the polyscape framework (Jackson et al., 2013), and its development is led by Victoria University. The model will be used for this research mainly because of its unique trade-off tool, which identifies trade-offs between multiple ecosystem services at once. Waterways in the Selwyn catchment have not been in a good state for some time now and as mentioned in the literature review, Lake Te Waihora/Ellesmere has been in the super trophic state due to agricultural activities within the catchment. LUCI suits this situation as it identifies positions within the catchment where agriculture could be managed to limit nutrient export to waterways.

It is a decision support tool that explores the impacts of land cover change on ecosystem services (Trodahl, Jackson, Deslippe, & Metherell, 2017). LUCI identifies existing features that require preservation as well as positions that require a change in land-use to improve ecosystem services. Individual ecosystem services can be assessed and currently, LUCI simulates seven ecosystem services: agricultural production, erosion risk and, sediment delivery, flood mitigation, carbon sequestration, habitat provision and water quality (nitrogen and phosphorus) (Jackson et al., 2013). Fig. 5 below shows how data are processed in LUCI.

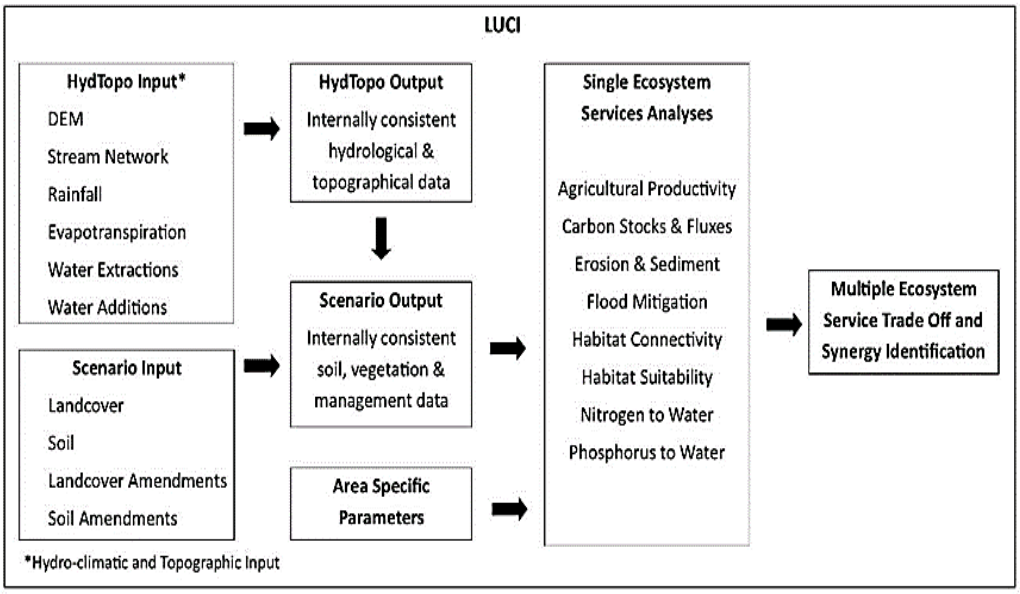

Figure 5: LUCI process diagram. Adapted from Figure 1 in Trodahl et al. (2017).

The model uses readily available data that is accessible online and can be amended with local knowledge (Trodahl et al., 2017). Input data requirements include a Digital Elevation Model (DEM), which represents the topography of a study area, land cover, and soil data. A 5x5 m to 10x10 m DEM resolution is recommended to get a detailed output.

Table 2: Summary of default input data for New Zealand (Trodahl et al. (2017)

Data name	Period covered	Data Type	Resolution	Information found on-line?
Digital Elevation Model (DEM)	2011	Raster	5 m x 5 m	Yes
Stream network	2010	Vector	Variable	Yes
Evapotranspiration	1960-2004	Raster	500 m x 500 m	No
Land Cover	2012/13	Vector	Variable	Yes
Soil	Based on soil surveys from 1930s-present.	Vector	Variable	Yes
Rainfall	1960-2004	Raster	1000 m x 1000 m	No

Land cover information must be compatible with the land cover types supported by LUCI. LUCI supports several land cover databases as shown in Table 3 below.

Table 3: Currently supported land cover inputs (adapted from the LUCI manual)

Data name	Data source code	Normal “unique identifier” fieldname	Available in:	Provider
LCM2007	13	INTCODE	UK	CEH
LCM2007 BH	14	FIELDCODE	UK	CEH
LCM2000	12	VALUE	UK	CEH
CCW Phase 1	11	CODE	Wales	NRW
LCDB1	21	LCDBCLASS	NZ	Landcare
LCDB2	22	LCDB2CLASS	NZ	Landcare
LCDB3	23	LCDB3CLASS	NZ	Landcare
LCDB4	24	CLASS_2012	NZ	Landcare
CORINE	51	GRID_CODE	Europe	EEA
NLCD 2011	31	VALUE	USA	MRLC

The soil information must correlate with the soil information supported by LUCI and LUCI supports several soil databases as shown in Table 4 below.

Table 4: Currently supported soil input (adapted from the LUCI manual)

Soil Product	Data Source Code	Linking Code	Available in	Provider
Full NATMAP	12	MAP_UNIT	UK	Cranfield
BGS Soils	13		UK	BGS
Fundamental Soils Layer	21	DOMNZSC	NZ	Landcare
S-Map	22		Part of NZ	Landcare
European Soils	51		Europe	
Global Soils	91		All globe	

Results generated by LUCI are presented in tables and maps. LUCI maps use a traffic light system to distinguish between ecosystem service provision categories. Green indicates positions with high existing ecosystem service provision which are recommended for protection, red indicates an opportunity to significantly improve service provision and orange indicates high existing provision with little opportunity to enhance it (Trodahl et al., 2017).

2.7.3.1 Pre-processing

Pre-processing is the first stage in processing data for use in LUCI. This is performed in two stages using the HydTopo and scenario input tools. The HydTopo tool is the first stage in pre-processing and it should be run once only for any site. The tool creates hydrological and topographical information required by the model. A consistent DEM is generated from the standard DEM provided as input data and this is done by filling up depressions in the DEM data and uses the AGREE method to burn river networks into elevation data (Jackson et al., 2013).

The scenario input tool generates land management data required by LUCI by linking land cover and soil data.

2.7.3.2. Individual tool description

LUCI currently supports seven ecosystem service models, which are explained in detail below.

2.7.3.3 Agricultural productivity

The tool examines the slope, aspect, drainage, and fertility of the land to determine the agricultural productivity status of the land.

2.7.3.3.1 Current agricultural utilisation

To determine current agricultural productivity, the model uses land cover data and considers all arable and improved grassland to be highly productive whilst bare ground and wetlands are considered not productive. Output results generated under the current agricultural utilisation are split into five different categories of production from very high to no production.

2.7.3.3.2 Predicted optimal utilisation

Predicted optimal agricultural utilisation is determined by the slope, fertility, drainage, and aspect of the land (Trodahl et al., 2017). Flat, well-drained and fertile areas are highly productive while steep or waterlogged areas are less suitable for agricultural production. Soil data such as soil texture, soil type, and soil structure are used to determine drainage and fertility, and the DEM is used to determine the aspect and slope. North facing slopes in the southern hemisphere are more productive.

2.7.3.3.3 Relative utilisation

Relative utilisation is calculated by comparing current and predicted agriculture to identify locations that appear to be over and underutilised.

2.7.3.3.4 Agricultural utilisation status

Agricultural utilization status is generated by combining the current and predicted optimal utilization. It identifies positions within the landscape that require preservation or change. Positions where land is used appropriately is considered worthy of protection while positions that are over or underutilized are considered for a change in management.

2.7.3.4 Water quality (nitrogen and phosphorus)

LUCI uses the export coefficient approach to model total nitrogen (TN) and total phosphorus (TP) export to water. Several water quality models use this approach in rural environments to estimate the export of non-point source pollution into waterways while in urban environments the event mean concentration (EMA) approach is used (Lin, 2004).

Water accumulation in the landscape is calculated from the rainfall and catchment characteristics, and cumulative N and P export is derived from export associated with land cover and land management of each grid cell. To determine the average accumulated total nutrient, the estimated ratio between cumulative total nutrient export and cumulative flow is used.

After running the water quality tool, LUCI generates several maps and tables in a pdf file format, which summarises the results of each analysis. The maps include nutrient load, nutrient accumulated load and nitrogen concentration in water.

2.7.*3.4.1* Development of export coefficients

Export coefficients (EC) are defined as a mass of contaminant per unit area measured in kg/ha/yr. (White et al., 2015). They are used to representing nonpoint source pollution linked with specific land cover and land use. ECs can be useful for regulatory purposes such as determining the impact of land use on water quality. Several methods have been used to determine nutrient export coefficients and a brief overview of the method used by McFarland and Hauck (2001) will be outlined.

This method was applied in the upper North Bosque River watershed in the USA. Firstly, major land uses of the catchment were determined, then flow and nutrient concentration data for thirteen sampling sites were collected. Multiple regression was used to estimate ECs for major agricultural land uses and measured nutrient loadings data from the sampling sites. Data from eleven sampling sites were applied in the multiple regression and the other two sites were reserved for validation. EC values from the literature were then compared against the calculated ECs. Thereafter, an empirical source model was developed using EC values obtained from the multiple regression as well as land use data to estimate loadings by source. The empirical source model was validated by comparing measured loadings to predicted loading using sites that were not included in the development of ECs. Finally, the Monte Carlo simulations were used for uncertainty analysis of the determined ECs (McFarland & Hauck, 2001).

2.7.3.5 Flood mitigation

This tool identifies positions within the landscape that can mitigate flooding. Positions with high infiltration and high-water storage capacity are regarded as suitable sinks for floodwaters. Land cover data are used to determine mitigation features, and land cover associated with woodland, wetland, bog, marsh, and scrub are considered suitable for flood mitigation. All areas where large amounts of flow are routed directly into waterways are treated as priority areas for change. The input data requirements for this tool includes a DEM and land cover (Jackson et al., 2013).

2.7.3.6 Erosion risk and sediment delivery

LUCI identifies areas at risk of erosion and areas at risk of contributing significant sediment loading to waterways. The model uses the Compound Topographic Index (CTI) to indicate erosion risk areas. CTI is defined as a measure of the soil moisture potential calculated from the DEM. It is calculated using the formula:

$$CTI = A \times S \times PLANC$$

Where:

A = Upslope drainage area (m^2)

S = Local slope (m/m)

PLANC = Platform curvature (1/100 m)

It combines the slope, overland flow magnitude and concentration to represent erosion potential of overland flow.

2.7.3.7 Carbon sequestration

This tool identifies positions in the landscape that are susceptible to carbon losses as well as identifying those areas that can be modified to store more carbon dioxide. The model uses the IPCC Tier 1 protocol to calculate carbon opportunity.

2.7.3.8 Trade-offs

Multiple ecosystem services can be compared to identify positions within the landscape where trade-offs exist. The trade-off tool identifies where opportunities exist to improve service delivery at the same time protecting those areas which currently deliver high level services (Jackson et al., 2013; Trodahl et al., 2017). Trade-off layers can be two-way, three-way, or four-way (Jackson et al., 2013).

2.8 A Comparison of LUCI vs SWAT

2.8.0 Introduction

This section will give an outline of the similarities and differences between the SWAT and LUCI models. The SWAT model was not used in this research, hence findings in this chapter for SWAT were obtained from reviewing the existing literature. The main aim of this comparison was to see how LUCI fits in with models that have been applied successfully and extensively across New Zealand, considering that, though it is still new, it has been applied successfully in some parts of New Zealand.

2.8.1 Similarities

Although the SWAT model is a hydrological modelling tool, the model has been used as a mechanism to help quantify Ecosystem Services (ES) in catchments (Vigerstol & Aukema, 2011), a similar function in which the LUCI model performs. Information obtained from the quantification of ES is important in determining areas that require protection and restoration to ensure adequate ES levels.

Both models use ArcGIS as an interface though SWAT can also use QGIS. QGIS is an open source GIS which is freely available and can be downloaded and used on any operating system (QGIS, 2019). ArcGIS is a commercial software which was developed by Environmental Systems Research Institute (ESRI). It is proprietary and can only be installed on a Windows system (ESRI, 2019). Access to both models is open and each model provides detailed documentation, which has contributed to the successful application in New Zealand and other countries.

The major input data requirements for both models are similar (topography, soils and land-use/cover) though the modelling processes are different. LUCI, however, uses land cover whilst SWAT uses land use as input data. The terms land cover and land use are closely related and are often used interchangeably. The difference between the two types of data is that land use shows how people utilise land whilst land cover data indicates physical land types such as forests, wetlands, and agriculture (Anderson, 1976). For the topography, LUCI requires a DEM resolution of between 5 x 5 m to 10 x 10 m to get a more detailed output though any DEM resolution can be used (Trodahl M, Jackson B, Deslippe J, & Metherell A, 2016). The SWAT model does not give specifications of the required DEM resolution. However, a study by Buakhao and Kangrang (2016) used three different DEM resolutions (5 m, 30 m, 90 m) to determine their impact on physical characteristics using the SWAT model. Results indicated slight differences in watershed size and shapes whilst a notable difference in the slope was shown. It was therefore recommended using a 30 m DEM resolution as it displayed better results compared to the other two.

To determine the nutrient load of an area, both models use the export coefficient approach, this approach has been explained in section 2.7.3.4.1.

2.8.2 Differences

LUCI uses soil type to determine the nutrient status of an area whilst SWAT uses land use. However, with LUCI this can now be changed manually as evidenced by results generated under scenario two, in which farm types were used to determine the nutrient levels in a catchment.

LUCI simultaneously models different spatial scales from farm to catchment and this is one of its strengths amongst other models. SWAT, on the other hand, operates at a catchment scale when quantifying ecosystem services (Vigerstol & Aukema, 2011) but as a hydrological model, it has been used at various spatial scales to simulate plot size as well as whole catchments (Radcliffe et al., 2015).

In default mode, LUCI uses the traffic light system on generated maps to distinguish between categories of ecosystem service provision. This system allows an easy interpretation of results. The colours can however be changed manually to suit individual preference. Output maps generated in SWAT are manually set to suit individual preferences.

Input data used in the SWAT model can be modified to suit current catchment conditions. For instance, the land-use file can be edited to reflect current management practices, such as fertiliser application and stage of plant/crop growth. In doing so, it automatically alters the export coefficient value associated with land-use. Another interesting point with the SWAT model is that each time a user enters data for a specific study area, data are updated within the SWAT database and it creates site-specific data for that study area. In other words, users build models within SWAT, which represent their specific study area. With LUCI, input data files cannot be altered.

LUCI houses a trade-off tool that sets it apart from other models. According to Bagstad et al. (2013), amongst other models used in a comparison, LUCI was the only model with a trade-off tool. This tool allows a comparison of multiple ecosystem services at once. It identifies positions where opportunities exist to improve service delivery at the same time protecting those areas which currently deliver high level services.

For calibration and uncertainty analysis, SWAT uses SWAT-CUP (Calibration and Uncertainty Programs). A program designed to integrate various calibration and uncertainty analysis programs using the same interface. It enables an easier and quicker calibration procedure for users. The program creates graphs for calibrated results and generates data for comparison. By contrast, LUCI splits a catchment into watersheds and produces quantitative data for each watershed. These data can be used for calibration purposes, but the calibration process is not done within LUCI.

In view of all that has been mentioned so far, there are several similarities between both models and LUCI also differs from SWAT in several important ways.

This chapter gave an overview of ecosystem services, the impact of agriculture on water quality, water quality legislation in New Zealand and described water quality models including LUCI. A comparison between LUCI and SWAT was given to see how LUCI fits in with models that have been used in New Zealand. In the next chapter, the methodology will outline the LUCI modelling process used to achieve the results of this study.

CHAPTER 3: METHODS

3.0 Chapter summary

This section outlines the methods used to achieve the research objectives in two study areas. As mentioned earlier in the introduction, the research was undertaken in the Kaituna and Selwyn catchments. The Kaituna was used as a pilot study to test and gain familiarity with the model and the Selwyn was used as the primary study area. The Kaituna was chosen for the pilot study because it is a smaller catchment with surface water sources whereas the Selwyn is a larger catchment with both surface and groundwater sources and various farming activities. Generally, these catchments are different regarding size, topography and land use. However, the objectives to be achieved in both catchments are the same. This chapter is divided into two main sections the first one describes the general modelling process of LUCI whilst the second one describes the steps taken to modify and run the model.

3.1 The Kaituna catchment

The Kaituna catchment is located on Banks Peninsula and is characterized by volcanic geology with soils rich in phosphorus (Fig. 6). Banks Peninsula is a remnant volcano which ceased erupting approximately six million years ago. The catchment is approximately 4 900 ha in size and is very important for *Ngāi Tahu* particularly for the *Koukourārata hapu* of Banks Peninsula who used the Kaituna Valley as their traditional pathway from *Koukourārata* (Port Levy) to Te Waihora, to gather *mahinga kai* (Te Runanga o Ngāi Tahu, 2015).

Within the catchment lies the Kaituna River, which flows down the steep-sided valley. The river is hill fed and feeds directly into Te Waihora. Because of the topography of the catchment, streams are generally steep, and high flows are experienced during rainfall events, which accelerate erosion and allow sediments to enter the stream. Therefore, the topography and erosion are contributing factors to the state of water quality in the catchment (Selwyn-Waihora Zone Committee, 2016).

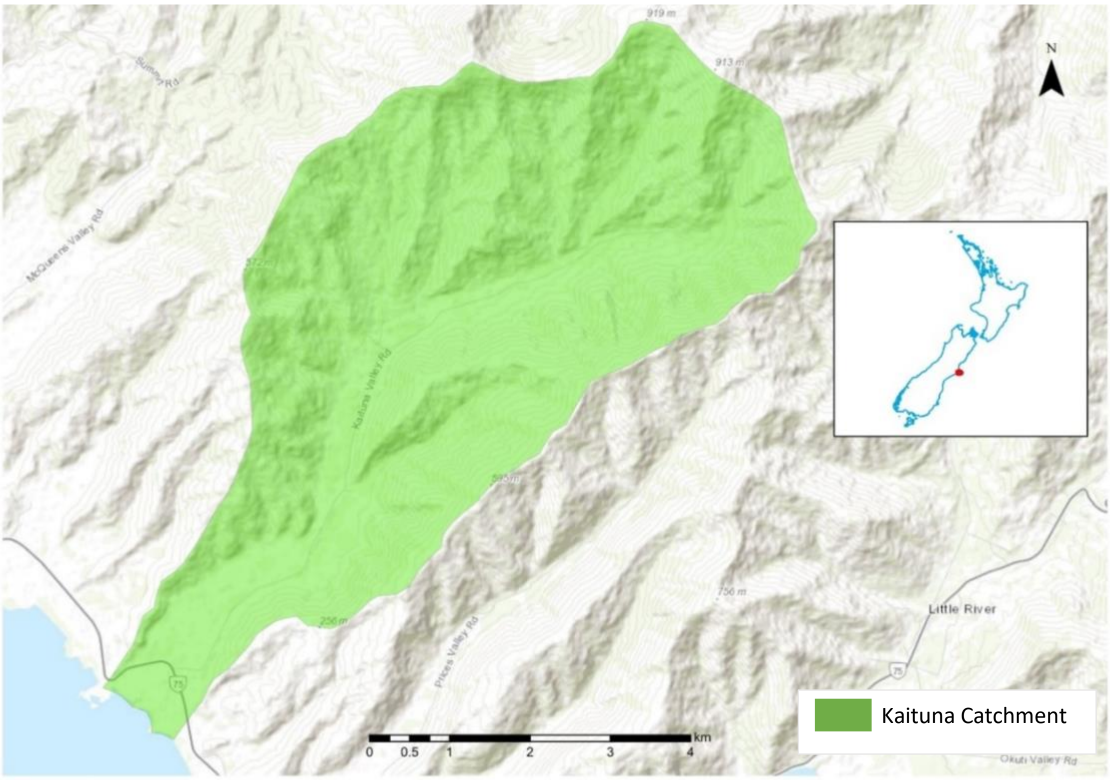

Figure 6: The Kaituna catchment map.

According to a water quality monitoring program done in the Kaituna catchment by Environmental Canterbury (ECan) between October 2014-October 2015, results indicated that faecal contamination levels had elevated more than nutrients and sediments. The water quality in the catchment did not meet recreational water quality standards; the reason behind high faecal contamination was identified as cattle having direct access to the waterways (Selwyn-Waihora Zone Committee, 2016). To control water quality in the catchment, fencing and riparian planting programs have been carried out.

3.1.1 Land-use/cover

The catchment comprises a diverse range of land uses, including orchards, vineyards, pastoral farming, and forestry, which add to the amenity value of the catchment. The orchards have a variety of exotic fruit trees and vines across the valley floor. The upper slopes provide recreation opportunities, which include access to Mount Herbert and the Pack Horse Hutt. Mt Bradley and Mt Herbert are the highest points on the Peninsula, forming a high wall that is the visual backdrop of the valley. There are several reserves within the valley and three of them are administered by the Department of Conservation (DOC) (Miskell, 2007). Fig. 7 below displays the various land use/cover types within the Kaituna catchment.

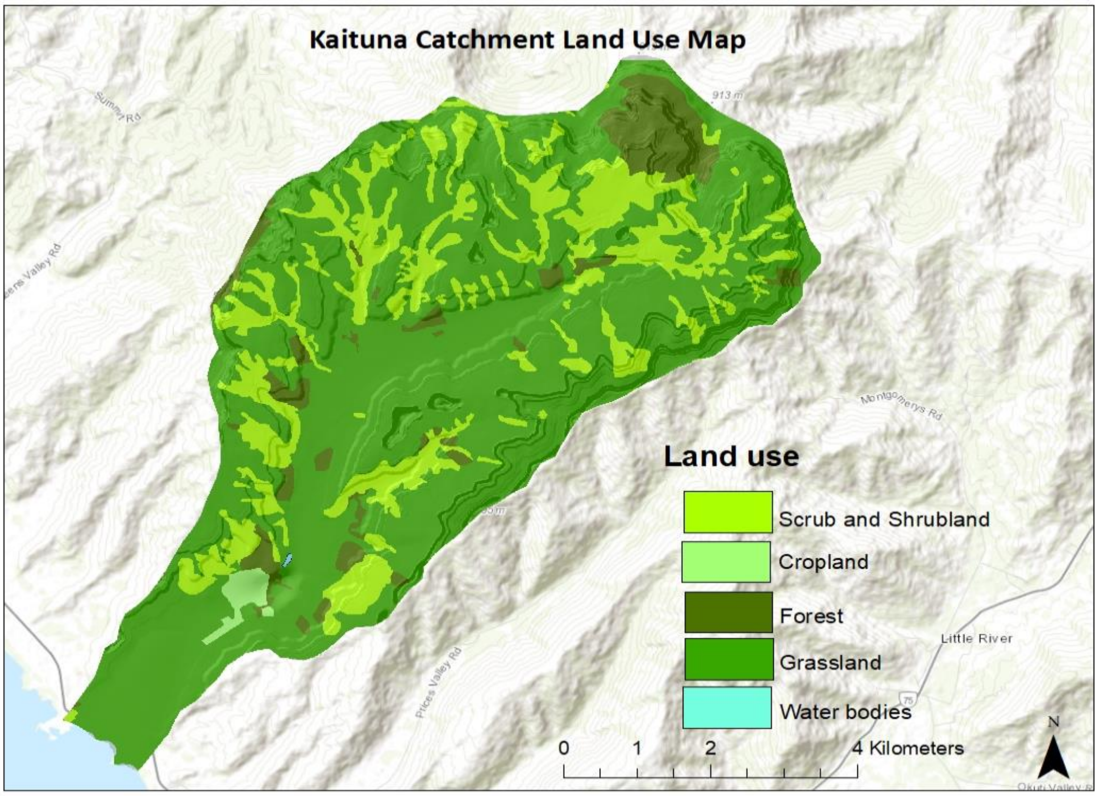

Figure 7: The Kaituna catchment land use map.

3.1.2 Soils

The catchment is dominated by Pallic soils, which are pale coloured and have a slow permeability as described by Hewitt, (2010) (Fig. 8). The other soil types occurring in the catchment include Brown, Melanic, Recent and Gley soils. A short description of these soils is given in Table 5.

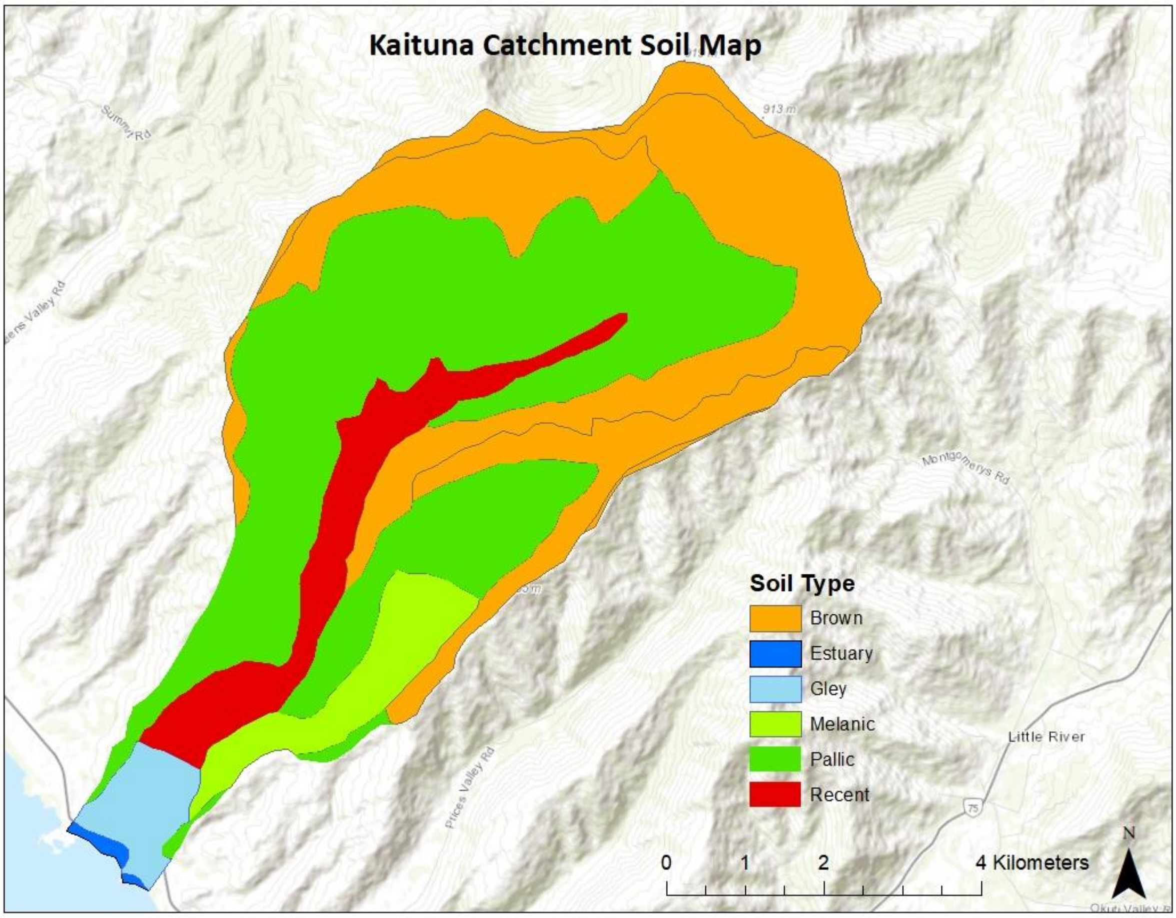

Figure 7: Kaituna catchment soil map.

3.1.3 Climate

The catchment lies on a high elevation area and receives higher rainfall than most parts of Christchurch and Banks Peninsula with an average of 800-1400 mm. Temperature varies with the season; during summer, the daily average maximum temperature ranges between 18-20°C and the daily average minimum in winter ranges between 3-5 °C (Macara, 2016).

Table 5: Soil Description (Adapted from Landcare soil orders)

Soil type	Description
Pallic	The soils are pale coloured due to low oxide content. They have a weak structure and high surface density horizons. During winter the soils are wet and dry in summer. They predominantly occur in the Eastern part of the North and South islands and Manawatu. Permeability is slow resulting in limited rooting depth. These soils are susceptible to erosion because of the high potential of slaking and dispersion. Nutrient content and base saturation levels are high to medium while organic matter, and oxide concentration is high. Pallic soils are divided into several soil groups based on factors such as drainage status, parent material chemical and physical processes.
Brown	These are the most extensive soils covering 43% of New Zealand. The subsoil is brown, yellow-brown coloured. Base saturation is low to moderate, and they contain large active populations of soil organisms. The soils are also broken down into several soil groups depending on parent material, chemical and physical characteristics.
Recent	Recent soils occur throughout New Zealand and cover 6% of the country. These soils are normally found on young land surfaces, unstable steep slopes and slopes mantled by young volcanic ash. They are deep-rooted and have a high plant-available water capacity. Inherent fertility and base saturation of recent soils is usually high.
Melanic	Melanic soils cover 1% of New Zealand. The top soils are black or dark grey, and these soils shrink on drying and swell on wetting. They also possess high inherent fertility.
Gley	These soils occur throughout New Zealand in low parts of the landscape where there are high ground water-tables and cover 3% of the country. Subsoils are light grey with reddish brown or brown mottles. Gley soils are greatly affected by waterlogging and are artificially drained for agricultural purposes.
Organic	These cover 1% of New Zealand and occur in wetlands or under forests that produce acid litter in areas with high precipitation. The bulk density, thermal conductivity, and bearing strength is very low whilst the total available water capacity and shrinkage potential is high.
Raw	Are very young soils, they occur in environments where top soil development is prevented by erosion, deposition or rockiness. They are found throughout New Zealand and found mostly in high mountainous areas, braided rivers, beaches and tidal estuaries covering 3% of the country. The soils are not fertile because they do not contain organic matter and nitrogen.

3.2 The Selwyn catchment

The Selwyn catchment is located in the Selwyn District in the South Island (Fig. 9). The headwaters of the Selwyn River are in the foothills of the Southern Alps of the South Island of New Zealand.

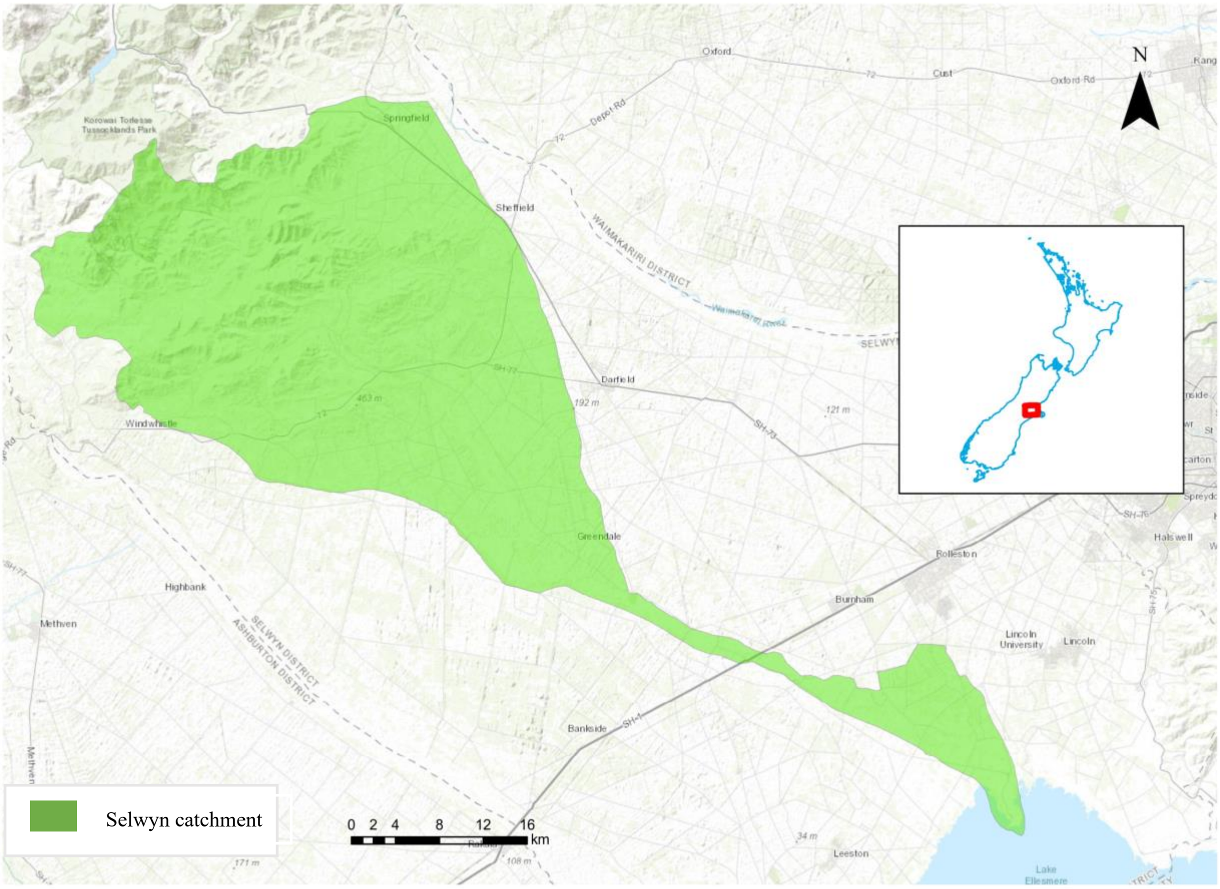

Figure 9: Selwyn catchment map.

The river crosses the alluvial Central Plains of the Canterbury region and discharges into Lake Ellesmere/Te Waihora. In the upper reaches the river loses surface water to the groundwater system while in the lower reaches when the groundwater table reaches the elevation of the riverbed the river gains flow from groundwater (Jenkins, 2017).

Lake Ellesmere/Te Waihora is a brackish coastal lagoon and is New Zealand's fifth largest lake by area. The lake provides a wetland habitat for an extensive range of birds, invertebrates and plant species and has huge cultural, ecological and commercial and recreational purposes. It is of cultural importance to *Ngāi Tahu* as a major *mahinga kai* site and an essential source of mana. Nationally and internationally, the lake is significantly known for its wildlife importance. A diverse range of exotic and indigenous fish such as trout, salmon, and inanga are supported by the lake (Kitto, 2010). The lake is regarded as one of the most polluted lakes in New Zealand and is categorised as super trophic which indicates excessive nutrients levels and high turbidity (Selwyn-Waihora Zone Committee, 2018) .

Influenced by accelerated agricultural activities, the Selwyn district is one of the fastest growing districts in New Zealand. Agriculture contributes 30% of the district's economic success but has led to a decrease in water quantity and less desirable water quality with high nitrogen concentrations in shallow groundwaters and lowland streams. Previous research has indicated that 95% of the total nitrogen loads in the Selwyn catchment have been contributed by losses from agriculture and that an estimate of 3,200 t/yr. of nitrogen load reaches Te Waihora (CWMS, 2005).

The primary contaminants in the Selwyn catchment include nitrogen, phosphorus, sediment, and microbial pathogens. Primary sources of nitrogen and phosphorus are excess fertilizer from agricultural fields and animal manure. High nitrate levels have health hazard impacts on humans and aquatic life (Minnesota Pollution Control Agency, 2008).

3.2.1 Land use/cover

Land use in the catchment comprises farming, livestock, recreation, and cropping. Land cover is dominated by grassland (Fig. 10), which comprises of a mixture of both high and low producing grassland. Cropland covers 6,025 ha of the catchment and it is spread around the catchment. Exotic forests cover a greater proportion of the catchment compared to the indigenous forests. The Selwyn River flows from the upper to the lower reaches into Te Waihora. Artificial surfaces in the catchment are comprised of built-up area, transport infrastructure, and urban parkland.

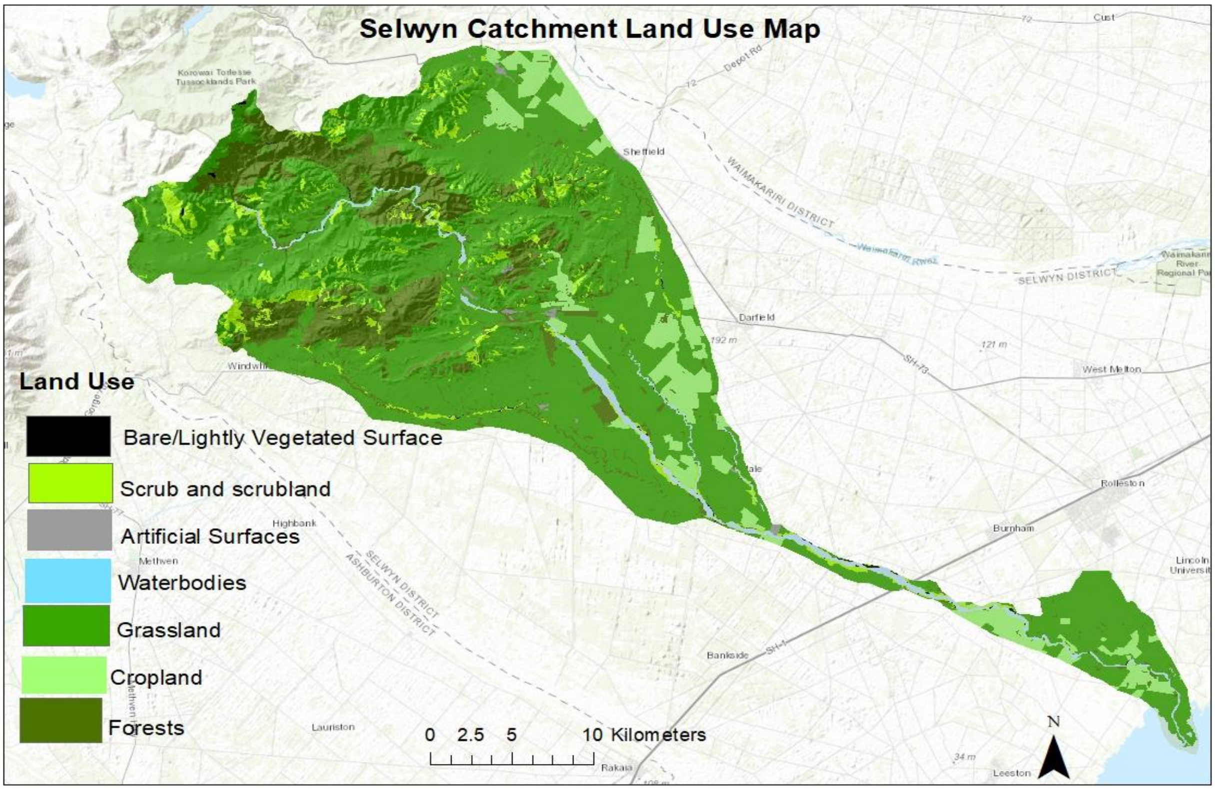

Figure 10. The Selwyn catchment land use map.

3.2.2 Soils

The Selwyn catchment is dominated by Brown Soils which are found within the upper reaches whilst the rest of the catchment has a mixture of Gley, Recent, Pallic, Organic, and Raw soils

(Fig. 11) (Refer to table 6 for soil descriptions). Raw and Organic Soils occupy a very small portion of the catchment and are located towards and in the lake.

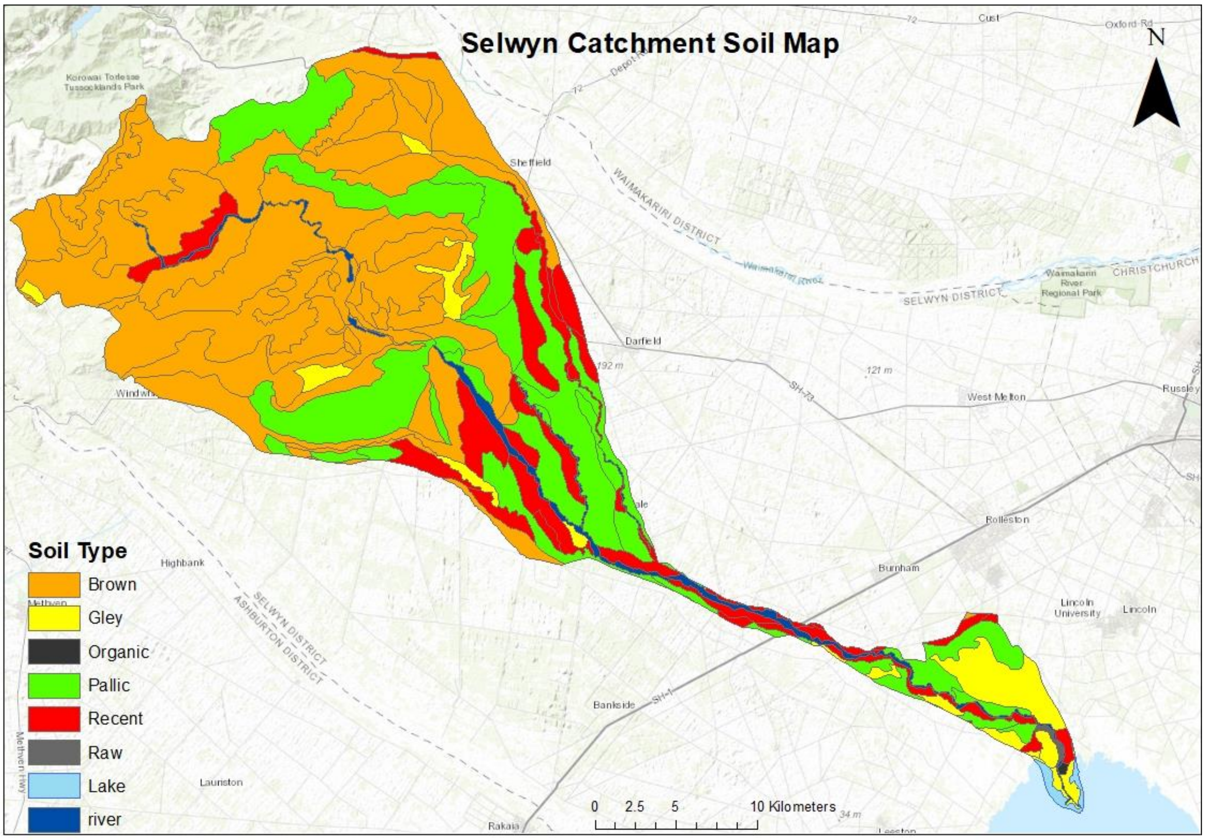

Figure 11. The Selwyn catchment soil map.

3.2.3 Climate

The climate varies significantly between seasons and is heavily influenced by the Southern Alps located west of the district. Annual rainfall ranges between 600 and 1000 mm with the highest rainfalls received at the foothills. The mean annual temperature is approximately 12°C. The Selwyn catchment falls within a district that is drier and sunnier than most parts of New Zealand (Cross, Dalziel, & Saunders, 2004).

3.3 Modelling process

The modelling process was divided into two scenarios. The first scenario used the LUCI model without any modifications done to the model codes and input data. With this procedure, LUCI uses soil type to determine the nutrient load in a catchment. Results obtained in scenario one did not provide a good reflection of the observed data obtained from the ECan water quality and monitoring website. Hence, in scenario two LUCI was modified so that farms in the Selwyn catchment are included in the input data and used to determine nutrient load in the catchment. The method in scenario one was applied in both catchments whilst scenario two was only applied in the Selwyn catchment because the Kaituna catchment has very few farming activities.

3.3.1 Modelling process (scenario one)

The steps taken in the modelling process scenario one are outlined below. Refer to appendix 1 for the flow diagram.

3.3.1.1 Data collation

Data were gathered from online sources specifically the Land Resource Information System (LRIS) and Land Information New Zealand (LINZ) websites. The input data layers used for both catchments include the DEM, land cover, soil, evapotranspiration and rainfall (Table 6).

For both catchments, a 5x5 m DEM which is recommended for use with LUCI was not readily available. Therefore, the required DEM for both catchments was created.

For the Kaituna catchment, the Christchurch 15 m DEM from LINZ was used. The DEM was clipped out into the study area and 10 m contours were created using the contour tool. This was done to derive elevation of the Kaituna catchment. The Topo to Raster tool was then used to create a 5 m DEM. The tools (Contour and Topo to Raster) used to create the DEM are ArcGIS tools found within the ArcMap interface. For this research ArcMap version 10.6 was used. The contour tool generates contour lines by joining points with the same elevation from a raster elevation dataset and the Topo to Raster tool Interpolates a hydrologically correct DEM (ESRI, 2019).

For the Selwyn catchment, the Selwyn catchment boundary was buffered to 100 m. The buffered layer was then merged to the catchment boundary and the boundary between the two was dissolved. 15 m DEMs from Koordinates were used for elevations and merged into one DEM. The developed boundary from the first step was used to clip out the Selwyn Catchment from the Christchurch-Timaru DEM. The contour tool was then used to derive elevation with a 2 m contour interval. To derive the new 5 m DEM, the Topo to Raster tool was used.

For the land cover, the landcover database 4 (LCDB4) was used and this was obtained from the Land Resources Information System (LRIS) portal. The Fundamental Soil Layer (FSL)- all attributes were used for soil data and were also obtained from the LRIS portal. Rainfall and evaporation layers for the periods between 1972-2014 and 1972-2016 respectively were used.

Table 6: Input data layers used for the Kaituna and the Selwyn catchment.

Data Layer	Data Used	Source
DEM	**1.**5 m Kaituna, 5 m Selwyn	LINZ
Land cover	**2.**Land Cover Database 4 (LCDB4)	LRIS
Soil	**3.**Fundamental Soil Layer (FSL)	LRIS
Rainfall	**4.**1972-2014	LRIS
Evapotranspiration	**5.**1972-2016	LRIS

3.3.1.2 Pre-processing

Pre-processing is the first stage in processing data using LUCI and this is performed in two stages, the hydtopo setup and the scenario analysis. The generated hydtopo, and scenario output folders are used as input folders in all individual ecosystem service tools.

3.3.1.3 Hydtopo setup

The input data used for this tool included the DEM, a study area mask, rainfall and, evapotranspiration. The other inputs have default values, which were not changed during the modelling process. Data are entered into the LUCI interface as shown in Fig 12. below.

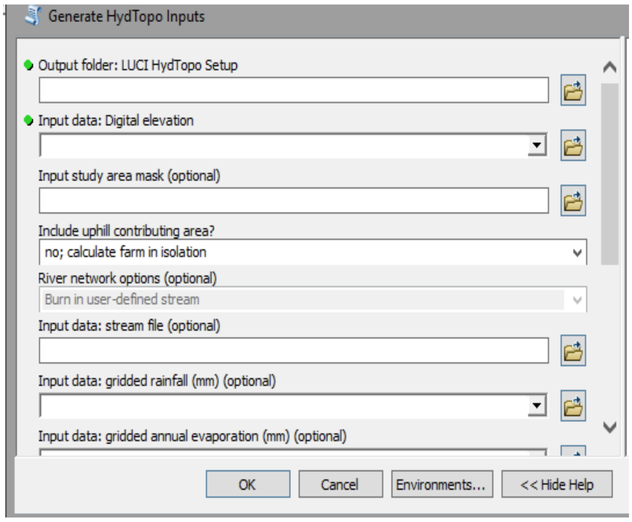

Figure 12: LUCI HydTopo Interface

3.3.1.4 Scenario setup

This tool uses the HydTopo output folder together with land cover and soil data as input data files. For the land cover and soil data, a linking code and data source for each data layer is required. These are used when converting data from ArcMap into LUCI. For land cover, the LCDB4 layer was used, therefore the data source for LCDB4 is 24 and the linking code is CLASS_2012. For soil data, the FSL was used and 21 was used as the data source and DOMNZSC as the linking code (refer to tables 3 & 4).

3.3.1.5 Agricultural productivity modelling

For agricultural productivity, the input data used include the HydTopo and scenario output folders. The other parameters for the agricultural interface have default values that can be changed to suit conditions of the study area, these parameters include slope thresholds which can be influenced by the resolution of the digital elevation model, elevation threshold, and fertility.

3.3.1.6 Nitrogen and phosphorus modelling

To run the water quality tools in LUCI (nitrogen to water and phosphorus to water), the input data used included the HydTopo and the scenario output folders. The other input parameters have default values that were not changed in this study.

3.3.1.7 Batch run

The batch run tool runs multiple ecosystem services at once; therefore, a selection of the desired ecosystem services should be done. In this case, nitrogen, phosphorus, and agricultural productivity were selected.

3.3.1.8 Trade-offs

The trade-off tool uses data from the batch run output folder to determine trade-offs. Trade-offs can be two-way or three-way. A two-way trade-off is when two ecosystem services are selected and run at once to allow a comparison between the two. For this research, a two-way trade-off was done between nitrogen vs agricultural productivity and phosphorus vs agricultural productivity.

3.3.2 Modelling process (Scenario two)

Steps taken to modify LUCI are explained below. Refer to the flow diagram in appendix 2 which displays steps taken to modify LUCI.

3.3.2.1 Step 1- removing overlapping polygons

The Selwyn farms layer was obtained online from the 2014 Agribase layer for Canterbury which is administered by Asurequality. This was clipped to the Selwyn catchment and later it was realised that some polygons within the layer were overlapping each other. To remove these overlaps, the find overlapping features tool was used to identify all overlapping polygons from the Selwyn farms layer and these were deleted using the following criteria:

- Farms with meaningless names such as "NEW" were removed if they fell on the same polygon with meaningful farm names such as dairy cattle farming.
- Polygons that occupied a smaller portion of overlapping polygons were removed.

3.3.2.2 Step 2-editing the lcdb4 layer

Since LUCI uses the linking code CLASS_2012 to identify land cover, CLASS_2012 and farm name fields were added into the Selwyn farms attribute table. The LCDB4 is one of LUCI's accepted land cover inputs hence the Update tool was used to combine the Selwyn farms polygon and the LCDB4 polygon to come up with the LCBD4_Update, which was then used as the land cover input data layer.

3.3.2.3 Step 3- editing the NZ_LCDB2 and NZ_LCDB4 layer

The NZ_LCDB2.DBF file contains data which are used by LUCI to make calculations of several ecosystem services. To this file, farm names, CLASS_2012, potential flood (pflood), potential agricultural productivity (PAGCLASS), N&P export coefficient (NEXCOF and PEXCOF) and N&P multiplier (nmult and pmult) values were added (see appendix 3). These values are used to calculate the nutrient load in a catchment. LUCI uses the NZ_LCDB4.DBF to identify land cover names using the CLASS_2012 values. These values and farm names were added to the NZ_LCDB4.DBF file.

For the Pflood values, the following values were used;

1- Indicates land cover that does not mitigate flow such as short rotation cropland.

2- Indicates land cover that mitigates floods such as some crops, forests, and shrubs.

3- Indicates water bodies such as lakes, ponds, rivers, and mangrove.

The description of values used in the PAGCLASS is shown in table 7 below.

Table 7: Description of PAGCLASS values

Value	**Description**
1	High productivity
2	Moderate productivity
3	Marginal productivity
4	Very marginal productivity
5	Negligible production value
6	Water bodies
7	Urban area

Nitrogen export coefficient values for livestock and crop farms were adapted from (Singh et al., 2017). Phosphorus values were adapted from the model itself (e.g. forest) and literature

(Reckhow, Beaulac, & Simpson, 1980; White et al., 2015). Estimate values were used for tourism, enterprises, beekeeping and unspecified farm types because EC values for these could not be found.

3.3.2.4 Step 4- running the model

The modelling process described in scenario one is the same process that was used at this point to generate results for water quality, agricultural productivity, and trade-offs.

This chapter has described how the model was used in two scenarios to achieve the objectives of the study. The next chapter will outline the results generated under both scenarios after running the water quality, agricultural productivity and trade-off tools.

CHAPTER 4: RESULTS

4.0 Chapter introduction

This chapter will give an outline of results obtained using modelling scenarios one and two to achieve objectives of this study. The chapter will be split into two sections; the first section will describe results obtained from the modelling process scenario one. This section will outline results generated for both the Kaituna and the Selwyn catchment. Section two will describe results achieved from the modelling process scenario two for the Selwyn catchment.

4.1 MODELLING SCENARIO ONE

KAITUNA CATCHMENT RESULTS

4.1.1 Nitrogen

After running the nitrogen tool, soils indicated to have a great influence on Total Nitrogen (TN) loads, with the highest TN loads located in positions with recent soils. These positions were found at the toe slopes of the catchment along the Kaituna River and TN loads in these areas amounted to 21 kg/ha/yr. Lowest TN loads were found in positions with estuary,pallic and, gley soils (Fig. 13).

Intrestingly, land-use activities did not appear to have any influence on TN loads as it was expected that positions under agriculture would have the highest TN loads. On further analysis, it was realised that the model does not incoorporate land-use activities in a catchment hence the research further modified the model to accommodate land-use activities.

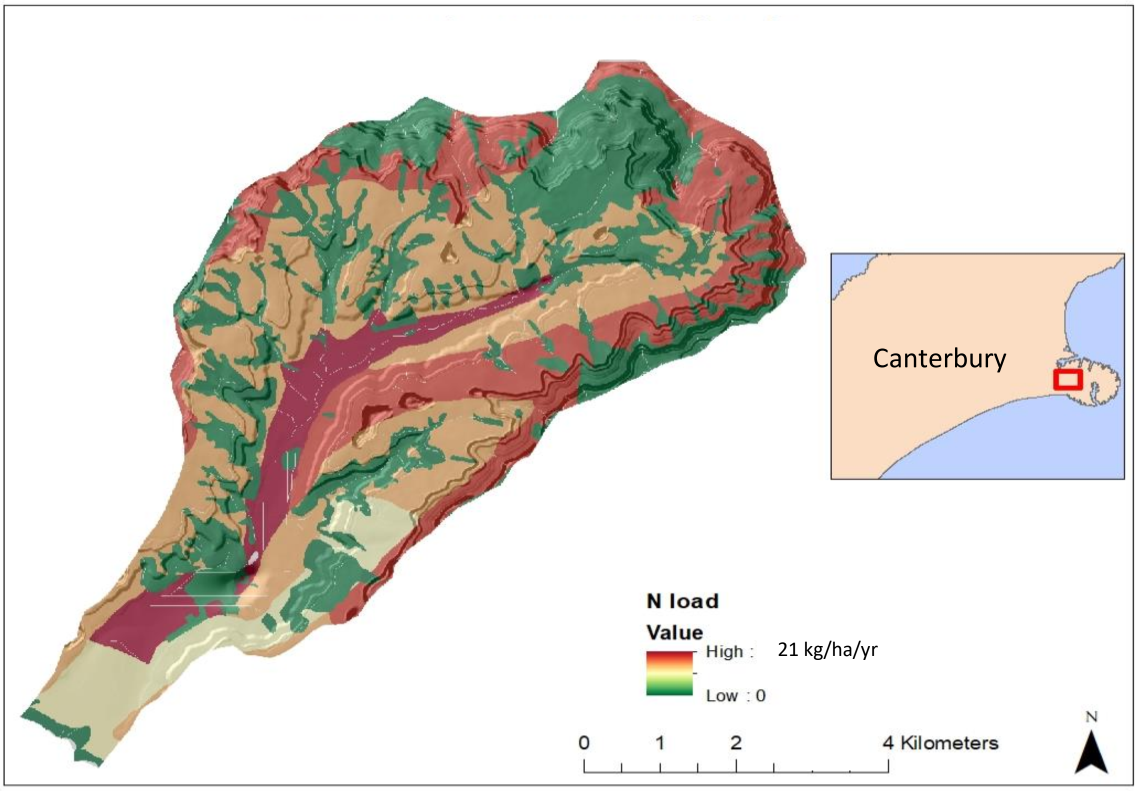

Figure 13. Kaituna Catchment nitrogen loads.

4.1.2 Phosphorus

The pattern of TP load results did not show any significant differences from results obtained for TN loads though for TP loads positions with the highest loads amounted to 0.59 kg/ha/yr which were lower than TN loads. Again the soils had a great impact on TP loads. Positions with recent soils had the highest TP loads whilst those locations with estuary,pallic and gley soils had the lowest TP loads (Fig. 14).

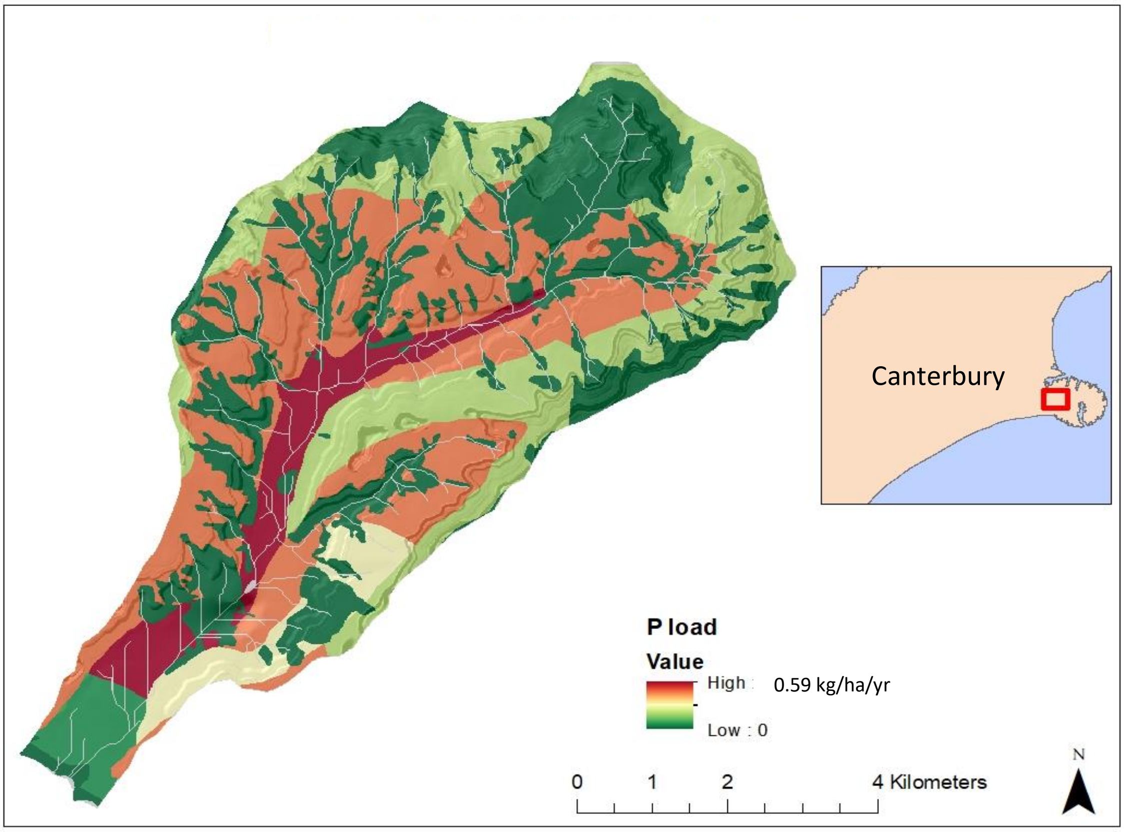

Figure 14: Kaituna Catchment phosphorus loads.

4.1.3 Agricultural productivity

4.1.3.1 Current agricultural productivity

To determine the current agricultural productivity, LUCI uses land cover data and considers all arable and improved grassland to be highly productive whilst bare ground and wetlands are considered not productive. Thirty square kilometres (65%) of the total catchment was considered to have a high agricultural productivity. This area is covered mostly with high producing exotic grassland. Twelve square kilometres (26%) of the catchment was considered unsuitable for agricultural production (Fig.15).

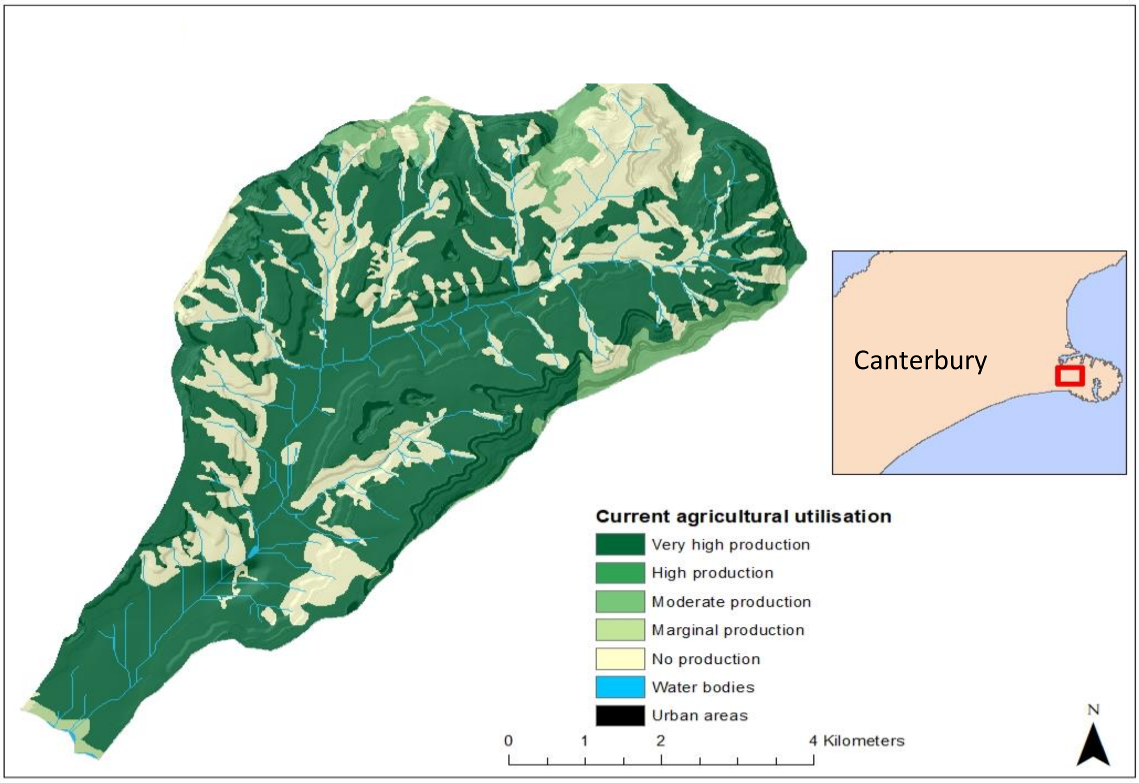

Figure 15: Kaituna catchment current agricultural utilisation.

4.1.3.2 Predicted optimum agricultural productivity

This is determined by the slope, fertility, drainage and aspect of the landscape. Flat, well drained and fertile areas are considered highly productive whilst steep or waterlogged areas are considered less suitable for agricultural production. Based on the analysis, thirty-four square kilometres (73%) of the catchment was considered marginal for agricultural productivity. This was influenced by the topography of the catchment. Only 1% of the entire catchment was considered to have a high agricultural productivity capacity and this is located along the Kaituna River (Fig. 16).

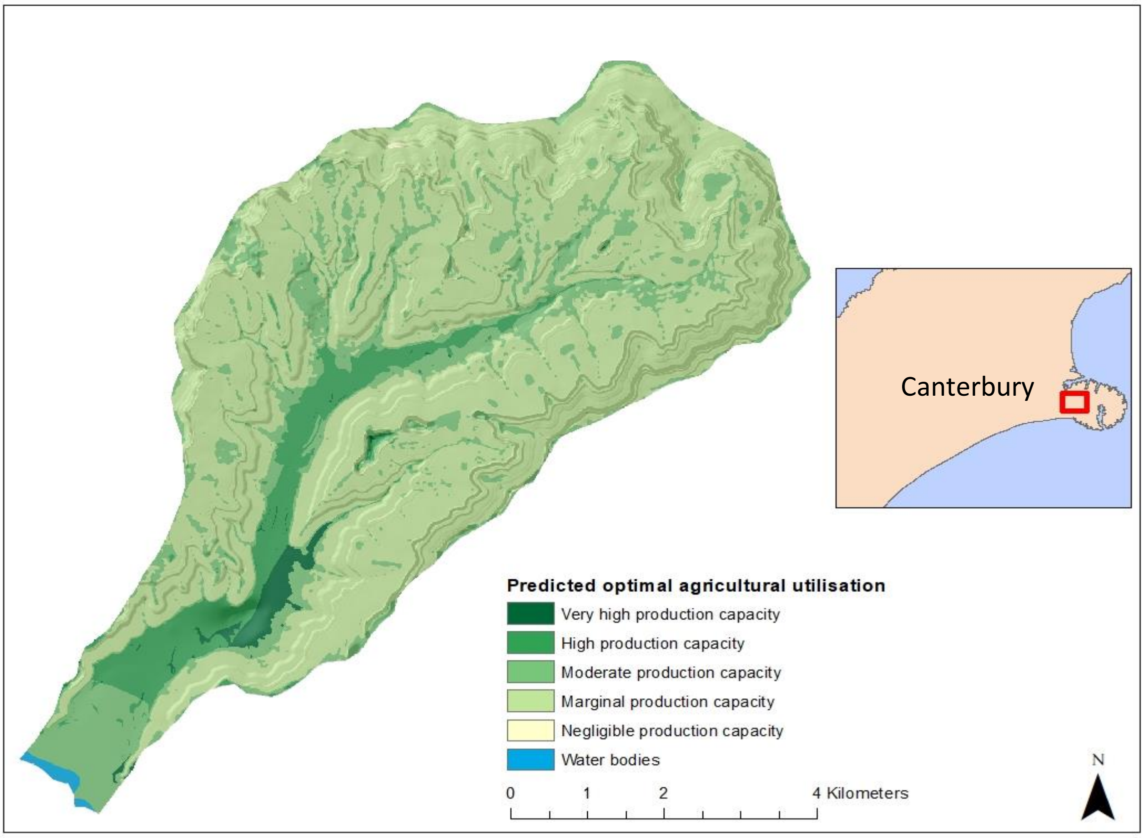

Figure 16. Kaituna catchment predicted optimal agricultural utilisation.

4.1.3.3 Relative utilisation

To assess relative agricultural production utilisation, LUCI compares current and predicted agricultural production utilisation to identify locations which appear to be over and underutilised. Generated results indicated that twenty square kilometres (45%) of the catchment has a very high utilisation. (Fig. 17).

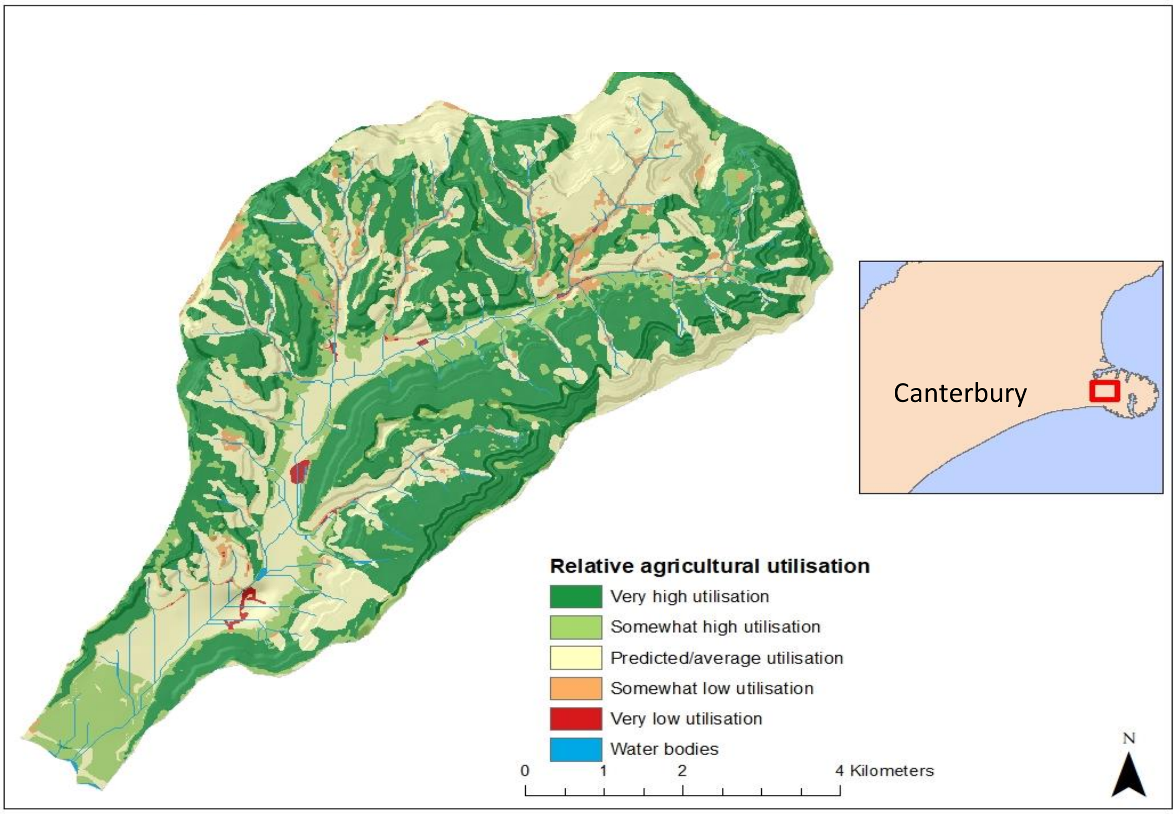

Figure 17: Kaituna catchment relative agricultural production utilisation.

4.1.3.4 Agricultural production utilisation

Agricultural production utilisation status is generated through combining the current and predicted optimal utilisation. It identifies positions within the landscape that require preservation or change. Positions that require change are those that are under or over utilised whilst those requiring preservation are positions at optimum utilisation. Results indicated that none of the catchment was at optimum utilisation. Twenty-one square kilometres (45%) was regarded as unutilised. These positions occupy a larger part of the catchment (Fig. 18).

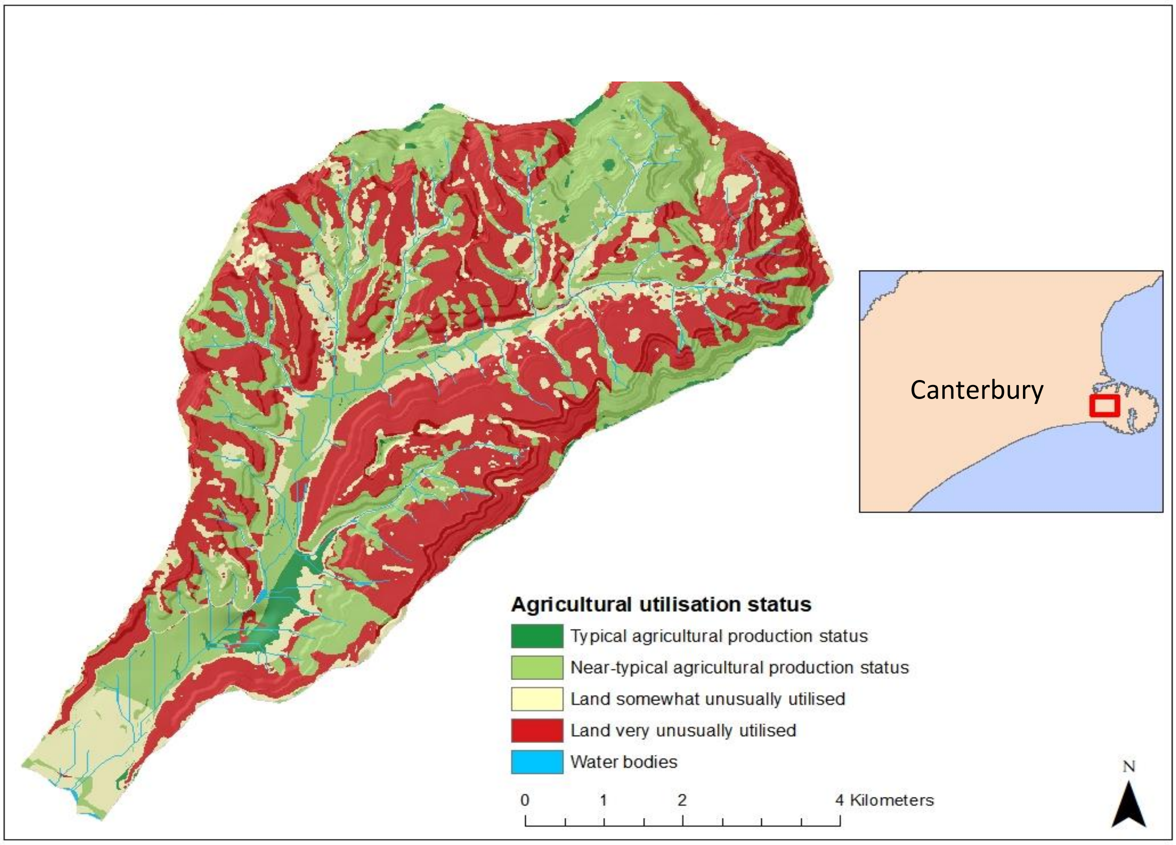

Figure 18. Kaituna catchment agricultural production utilisation.

4.1.4 Trade-offs

The trade-off tool identifies locations where opportunities exist to improve service delivery while at the same time protecting those positions where service delivery is high. A two-way trade-off was carried out between agricultural productivity vs nitrogen and agricultural productivity vs phosphorus.

4.1.4.1 Agricultural productivity vs nitrogen

Two square kilometres (46%) of the total catchment offers an excellent opportunity to improve both TN export and agricultural productivity. From the analysis, there were no positions within the catchment were both TN export and agricultural productivity had a high provision (Fig. 19).

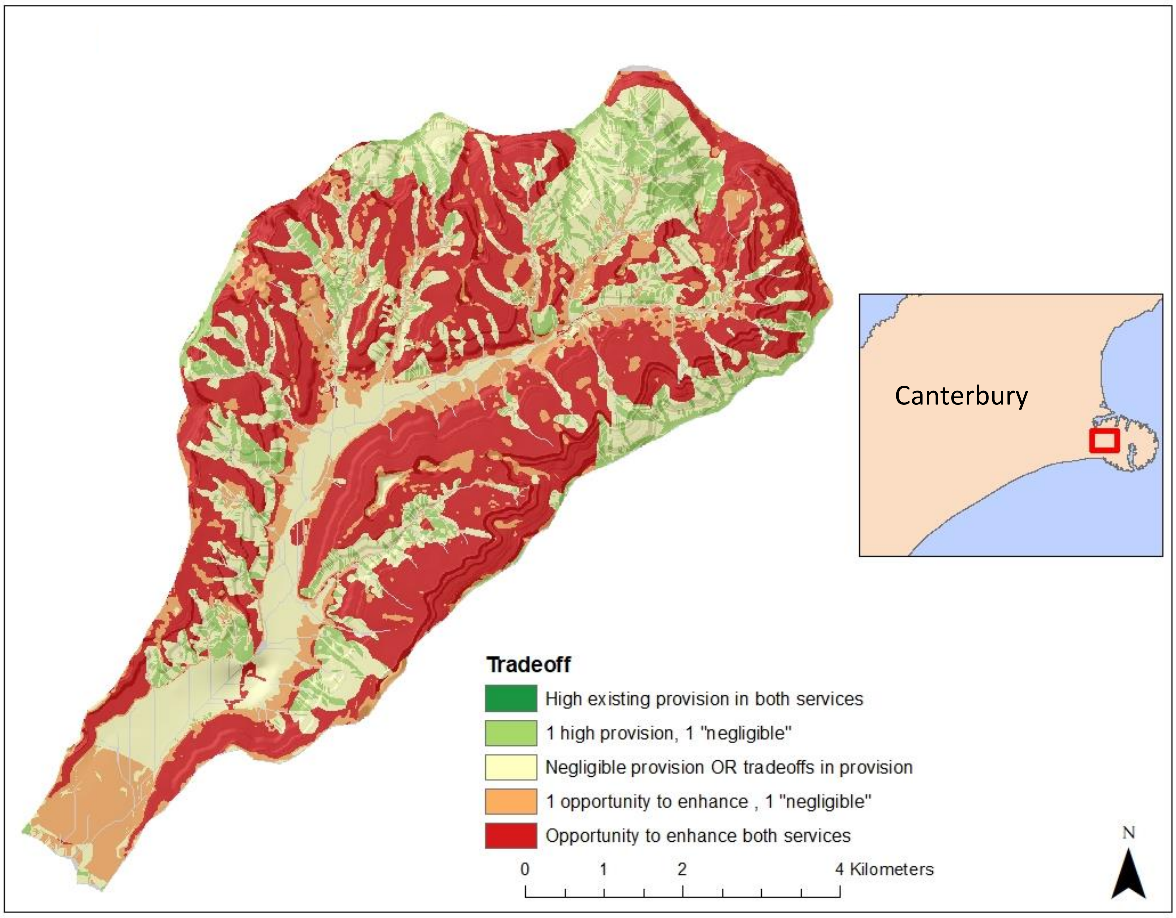

Figure 19. Kaituna catchment agricultural production vs nitrogen trade-offs.

4.1.4.2 Agricultural productivity vs phosphorus

No significant differences where found between agricultural production vs nitrogen and agricultural production vs phosphorus trade-offs. Two square kilometres (39%) of the total catchment had an excellent opportunity to improve both TP export and agricultural productivity and no positions within the catchment provided a high provision of both TN export and agricultural productivity (Fig. 20).

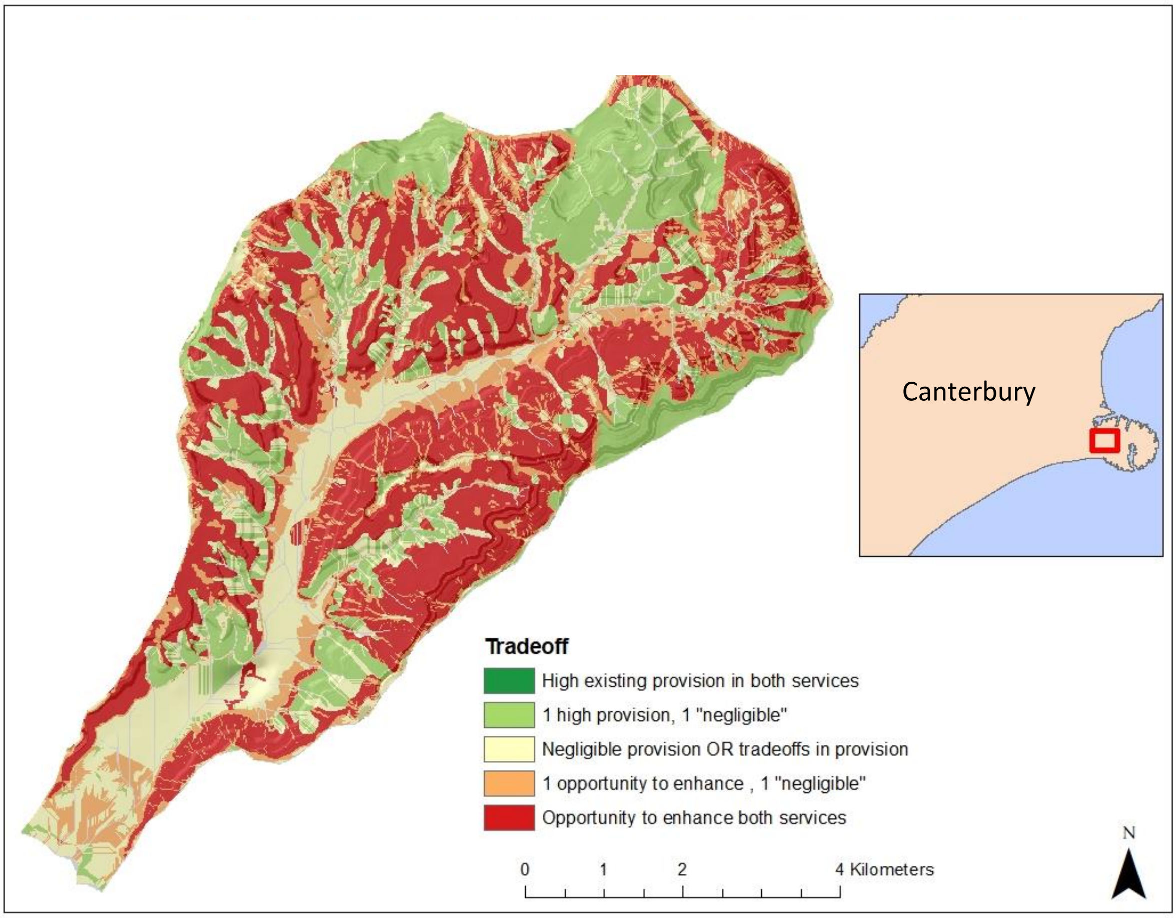

Figure 20. Kaituna catchment agricultural production vs phosphorus trade-offs.

As stated before, the Kaituna catchment was used to test run the model. The same LUCI tools used in the Kaituna catchment were also used in the Selwyn catchment the main study area.

THE SELWYN CATCHMENT RESULTS

4.1.5 Nitrogen

Generated TN loads indicated that positions with the highest TN loads amounted to 21 kg/ha/yr. As noted from results obtained in the Kaituna catchment, further analysis in the Selwyn catchment revealed that soils had strong influence on nitrogen load. Areas with Brown and Pallic soils had the lowest TN loads whilst positions associated with Recent soils had the highest TN loads.

The topography of the catchment had an impact on TN loads. Part of the upper catchment is comprised of foothills and it is in these positions were the lowest TN loads were obtained. The rest of the catchment is relatively flat and in these positions TN loads ranged from lowest to highest. Again, as shown in the Kaituna catchment, land-use activities did not appear to have any major impact on nitrogen load. It is apparent from the analysis that the model does not take into account any land-use activites (Fig. 21).

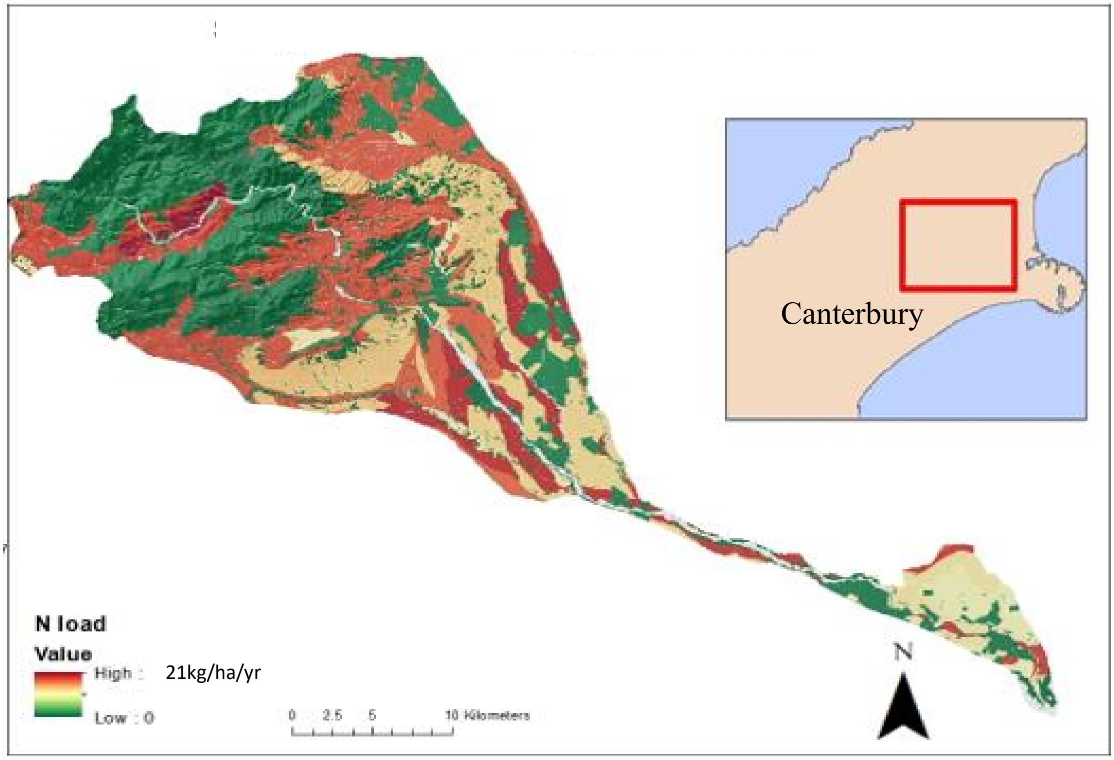

Figure 21. Selwyn catchment nitrogen loads.

4.1.6 Phosphorus

TP loads displayed a similar pattern with TN loads. 0.59 kg/ha/yr of TP loads were obtained in positions with the highest loads. The soils had a major impact on TP loads. Areas with brown soils had the lowest TP loads whilst those associated with recent soils had the highest TP loads.

Further analysis showed that the topography of the catchment had an impact on TP loads. Positions situated uphill of the foothills had the lowest TP load whilst the rest of the catchment had a combination of lowest to highest (Fig 22).

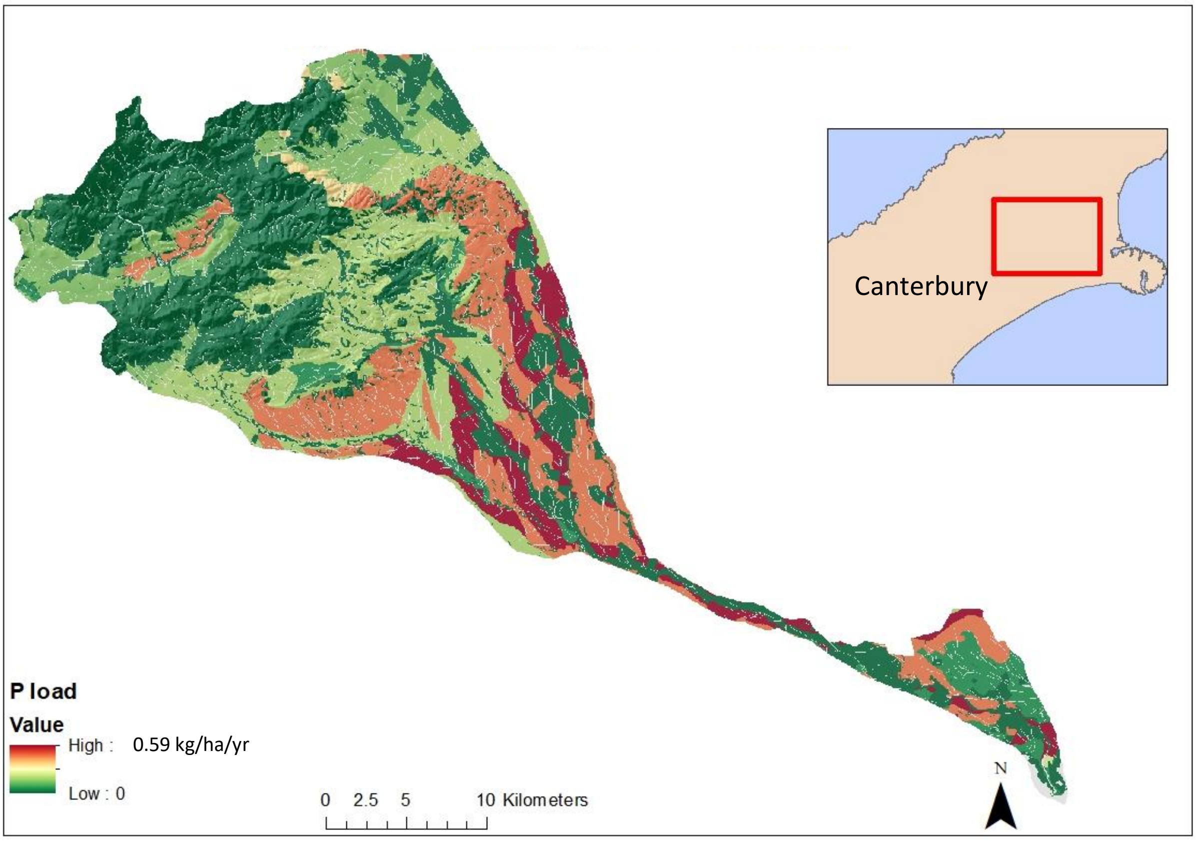

Figure 22. Selwyn catchment phosphorus loads.

4.1.7 Agricultural productivity

4.1.7.1 Current agricultural utilisation

Four hundred and sixty nine square kilometres (61%) of the Selwyn catchment was considered highly productive for agricultural production. This was influenced by the land cover type which is predomintantly grassland. LUCI identifies locations with improved grassland as highly productive. One hundred and fifty five square kilometers (20%) was regarded unsuitable for agricutural production. These areas were either bare ground or wetlands (Fig. 23).

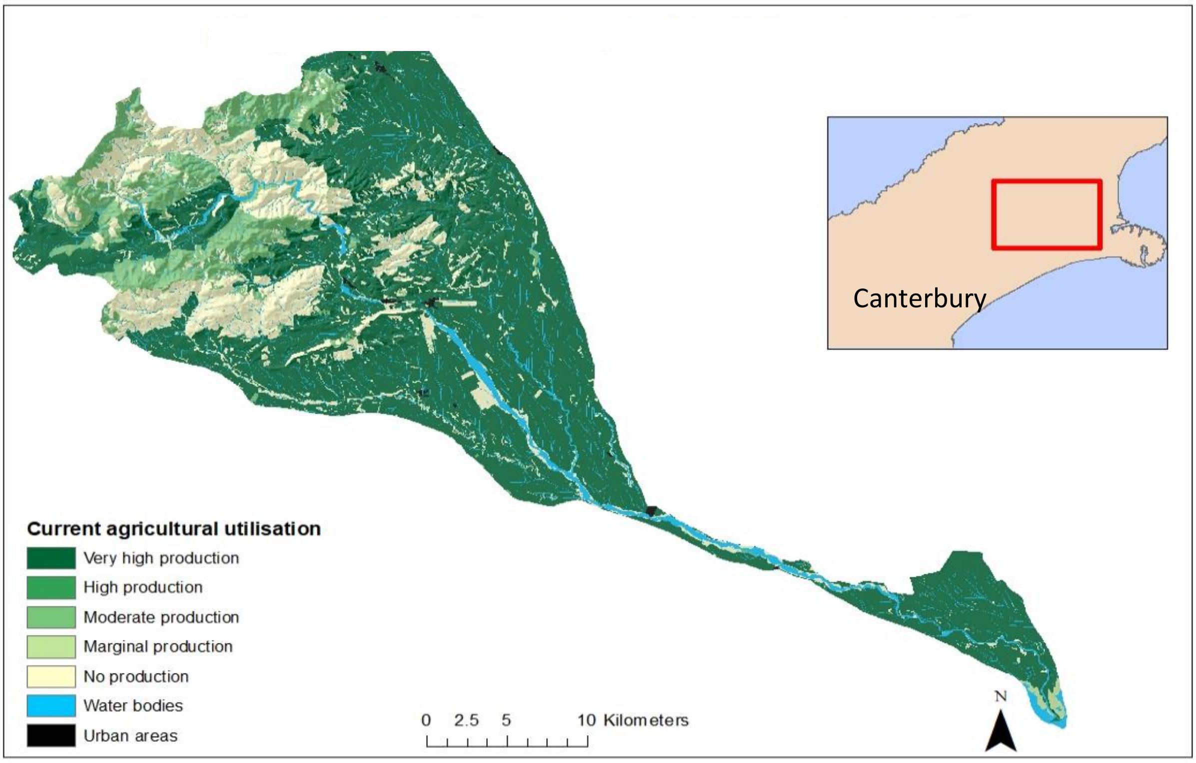

Figure 23. Selwyn catchment current agricultural utilisation.

4.7.1.2 Predicted optimum agricultural utilisation

Based on this analysis, only fifty five square kilometers (7%) of the total catchment was considered very productive. These positions are considered to be fertile, have good drainage and have a gentle slope. Two hundred and sixty three square kilometers (34%) was regarded as marginal for agricultural production. These areas were located in the upper catchment at the foothills and towards the lake. The upper catchment is steep and considered unsuitable for agricultural production and gley soils found torwards the lake are affected by waterlogging and LUCI considers these areas unsuitable for agricultural production (Fig. 24).

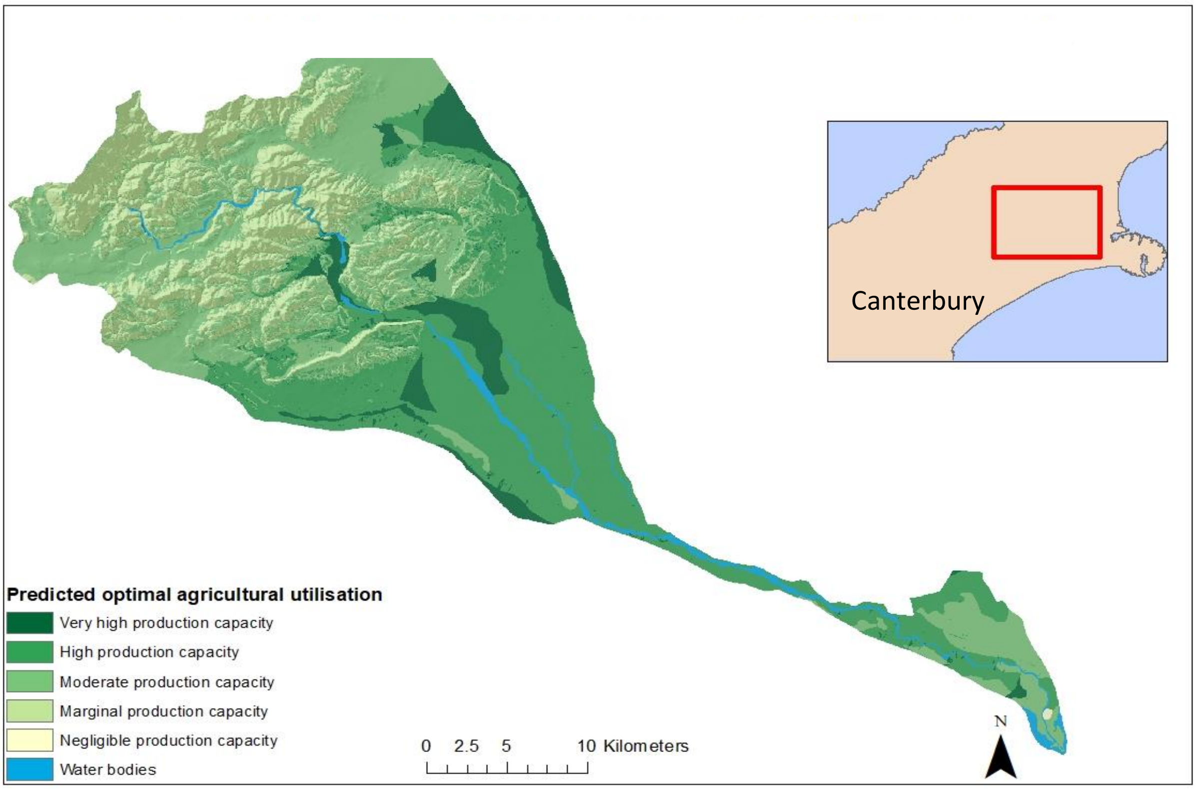

Figure 24. Selwyn catchment predicted optimal agricultural utilisation.

4.1.7.3 Relative agricultural utilisation

Only 26km^2 (4%) appears to be highly utilised. These positions are found in the upper catchment around the foothills. Forty eight square kilometers (6%) was regarded as significantly underutilised. These positions are found in small portions around the catchment (Fig. 25).

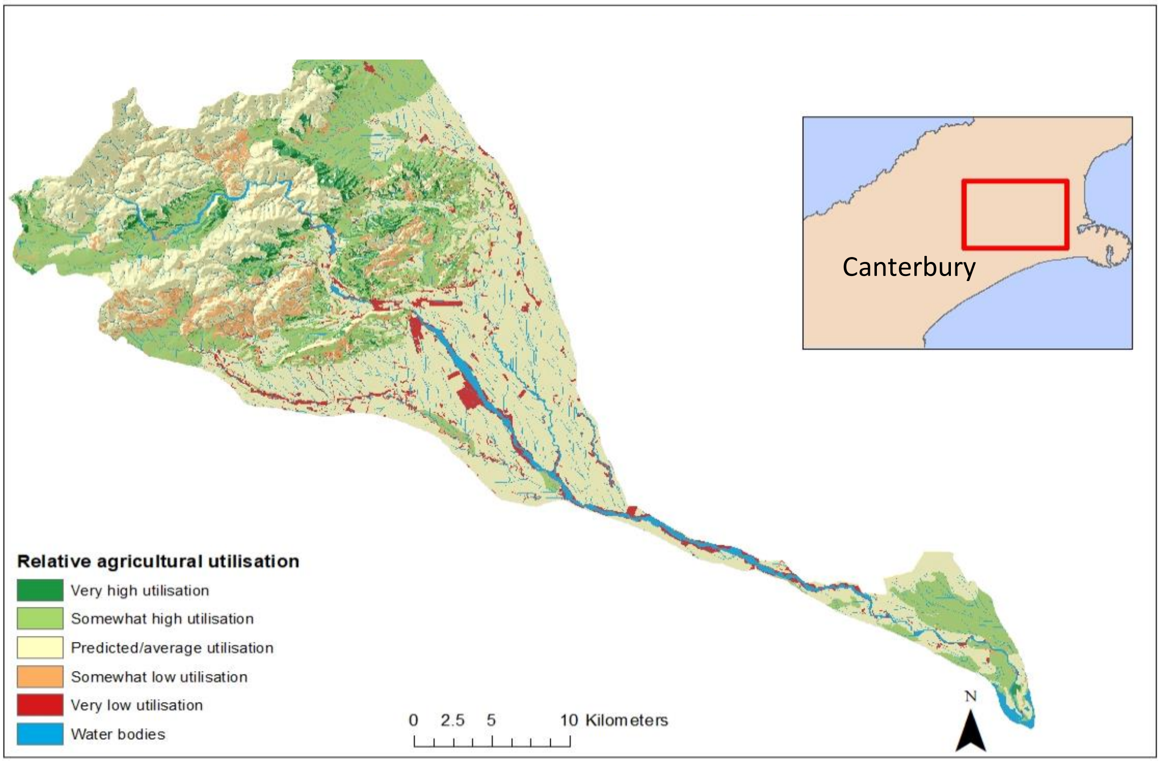

Figure 25. Selwyn catchment relative agricultural utilisation.

4.1.7.4 Agricultural production utilisation

Seventy square kilometers (9%) of the catchment was considered to be at optimum utilisation for agricultural productivity. These areas are small and are located in the upper and central part of the catchment. Fifty two square kilometers (7%) was regarded as land that is unusually utilised (Fig. 26).

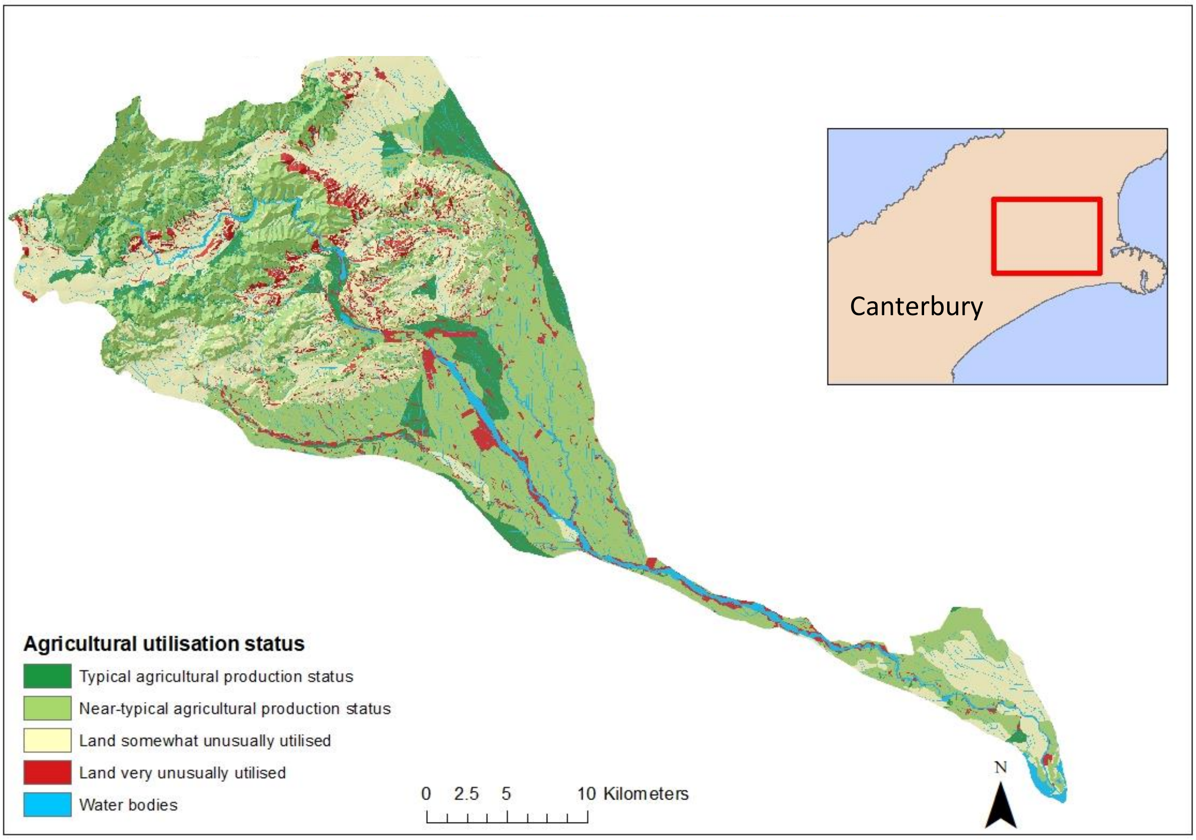

Figure 26. Selwyn catchment agricultural utilisation status.

4.1.8 Trade-offs

4.1.8.1 Agricultural productivity vs nitrogen

A two-way trade-off between agricultural productivity and nitrogen revealed that one km^2 (6%) of the total catchment provided an excellent opportunity to improve both agricultural productivity and TN export. There were no positions in the catchment which offered an excellent provision of both TN export and agricultural productivity (Fig. 27).

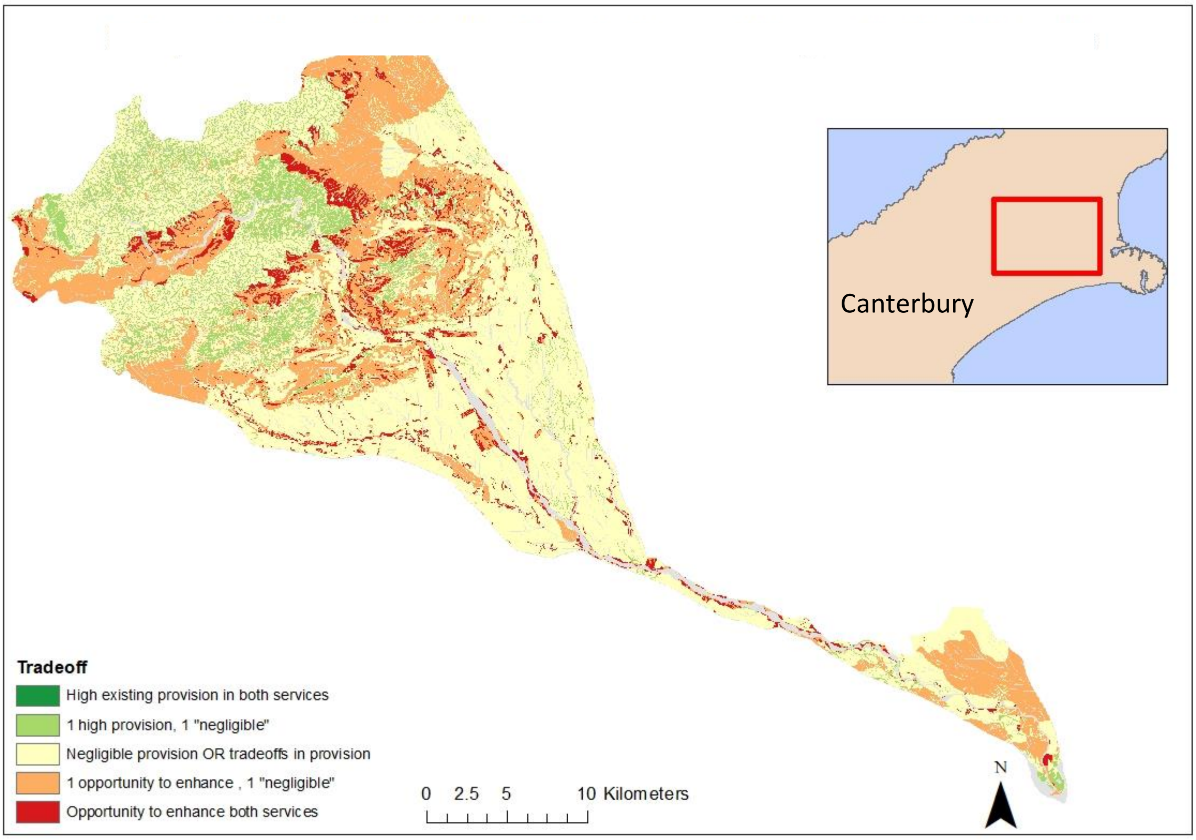

Figure 27. Selwyn catchment agricultural production vs nitrogen trade-off.

4.1.8.2 Agricultural productivity vs phosphorus

As shown in TN and TP loads results, not much difference was shown in trade-offs between agricultural productivity vs nitrogen and agricultural productivity vs phosphorus. One square kilometre (5%) of the total catchment provided an excellent opportunity to improve both TP export and agricultural productivity and there were no positions within the catchment which offer an excellent provision of both TP export and agricultural productivity (Fig. 28).

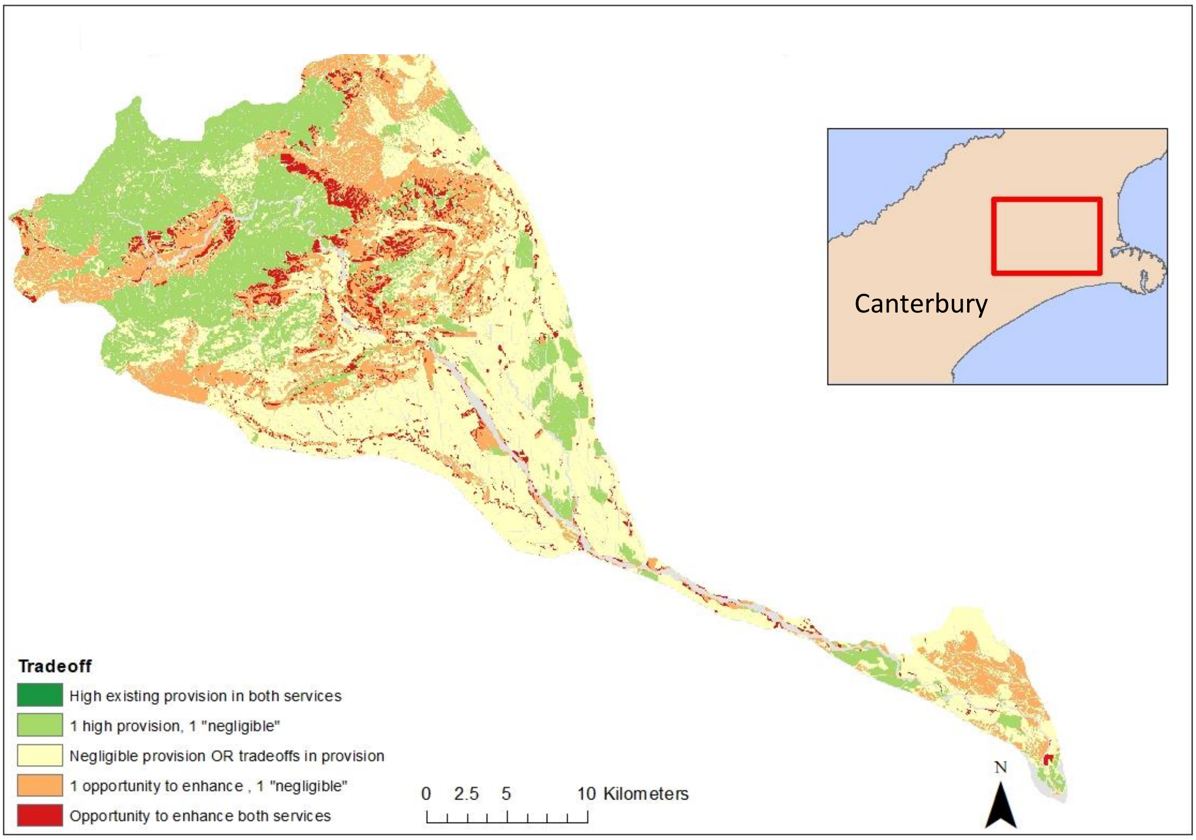

Figure 28: Selwyn catchment agricultural production vs phosphorus trade-off.

4.2 Modelling scenario two

4.2.1 Nitrogen

After running the nitrogen tool, positions with the highest TN loads had a total of 37 kg/ha/yr. Land use appeared to have a strong influence on generated outputs. Positions with dairy cattle farming had the highest nitrogen loads whilst those with farm types listed as bee keeping, tourism, and native bush had the lowest TN loads.

Further analysis revealed that the topography had an impact on TN loads. Positions located in the upper catchment, uphill on the foothills had the lowest TN loads. The rest of the catchment had TN loads ranging from low to highest.

Under this scenario, the soils did not have much impact on TN load (Fig. 29).

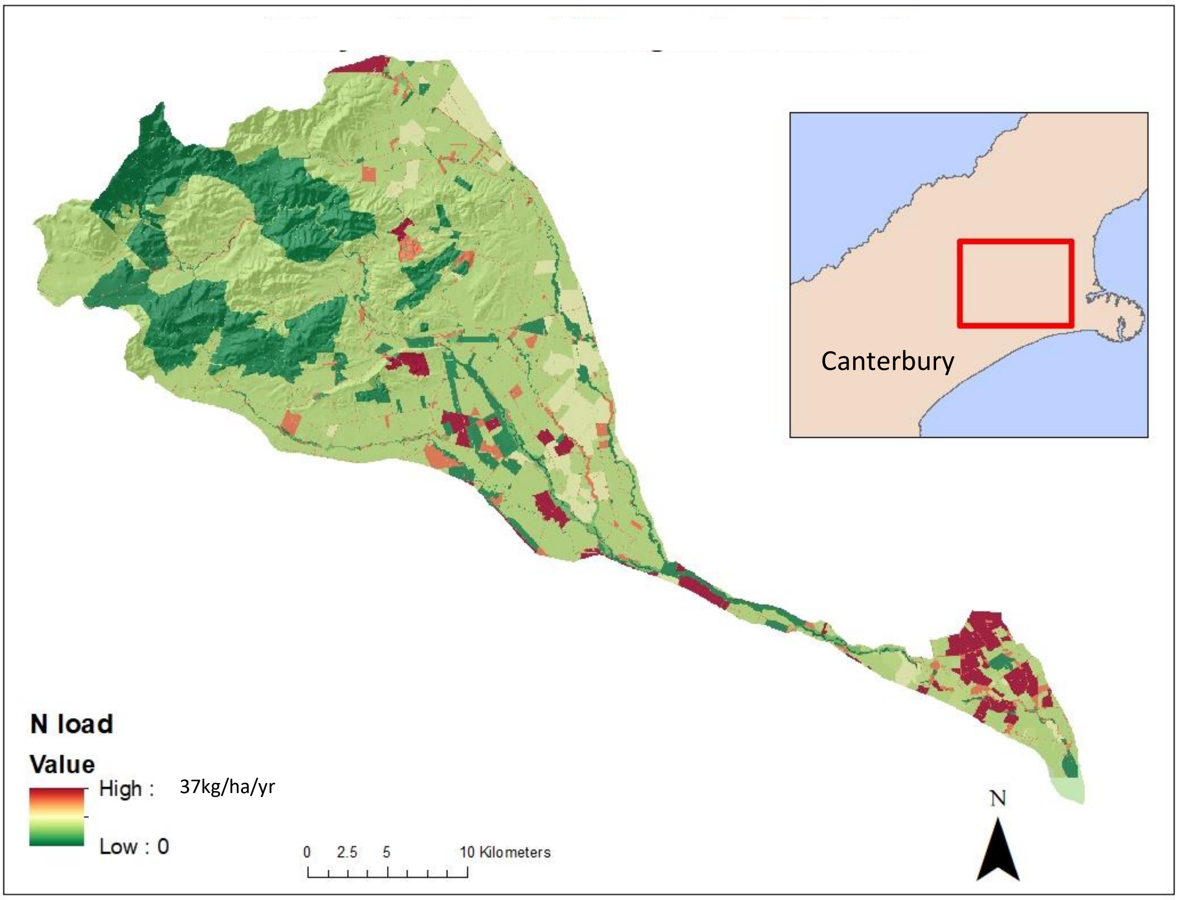

Figure 29. Selwyn catchment nitrogen loads.

4.2.2 Phosphorus

As evidenced above, land use also had a great impact on TP load. 2.2 kg/ha/yr of TP was obtained on positions with the highest TP loads. Locations under dairy cattle farming had the highest TP loads whilst those under bee keeping, tourism, enterprises, and native bush had the lowest TP loads.

The topography had an influence on TP load. Positions situated uphill on the foothills had the lowest TP loads whist the rest of the catchment ranged from low to highest TP loads (Fig. 30).

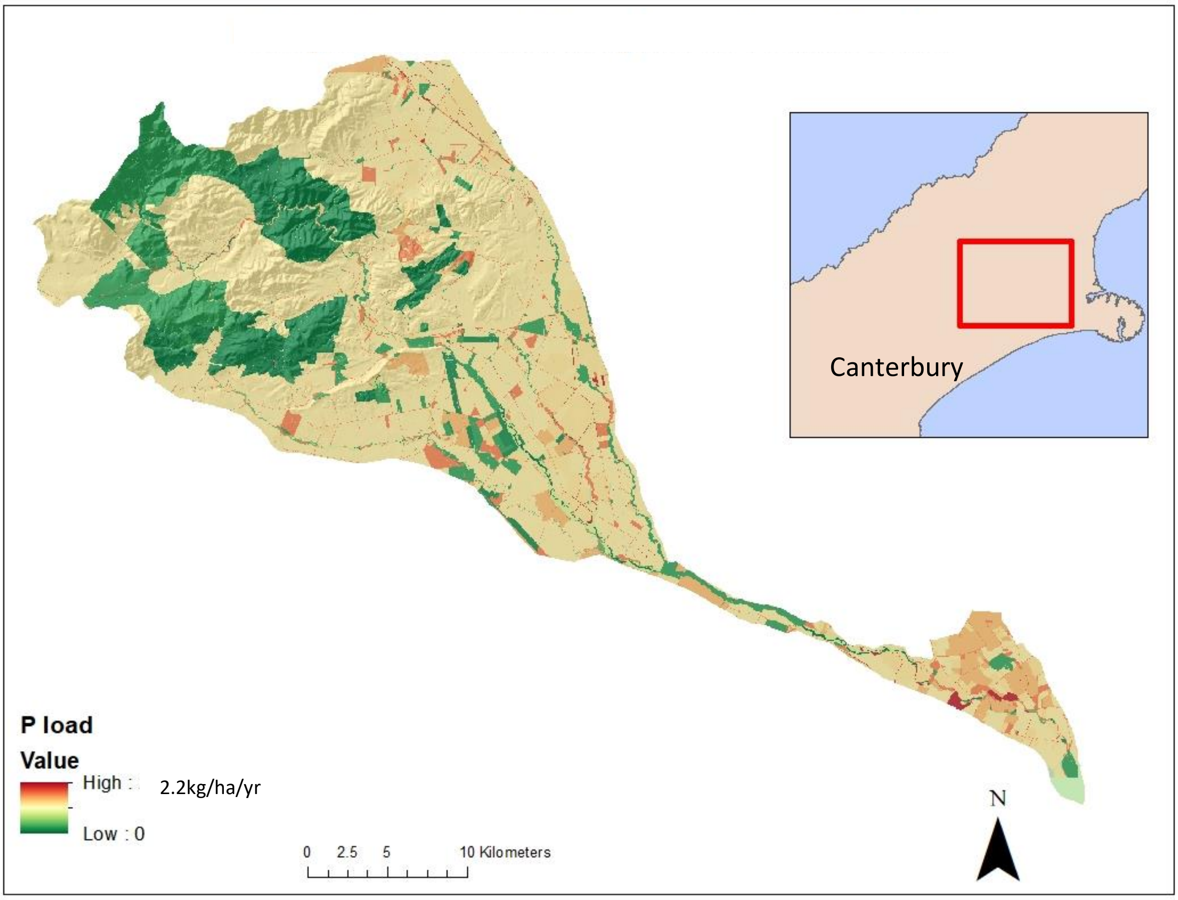

Figure 30. Selwyn catchment phosphorus load.

4.2.3 Agricultural productivity

4.2.3.1 Current agricultural productivity

Five hundred and ninty nine square kilometers (78%) of the total catchment was regarded as highly productive for agricultural production. This was determined by grasslands which occupy these areas and are regarded as highly productive by LUCI. One hundered and thirty seven square kilometers (18%) was considered as unsuitable for agricultural productivity. These areas were either bare ground or wetlands (Fig. 31).

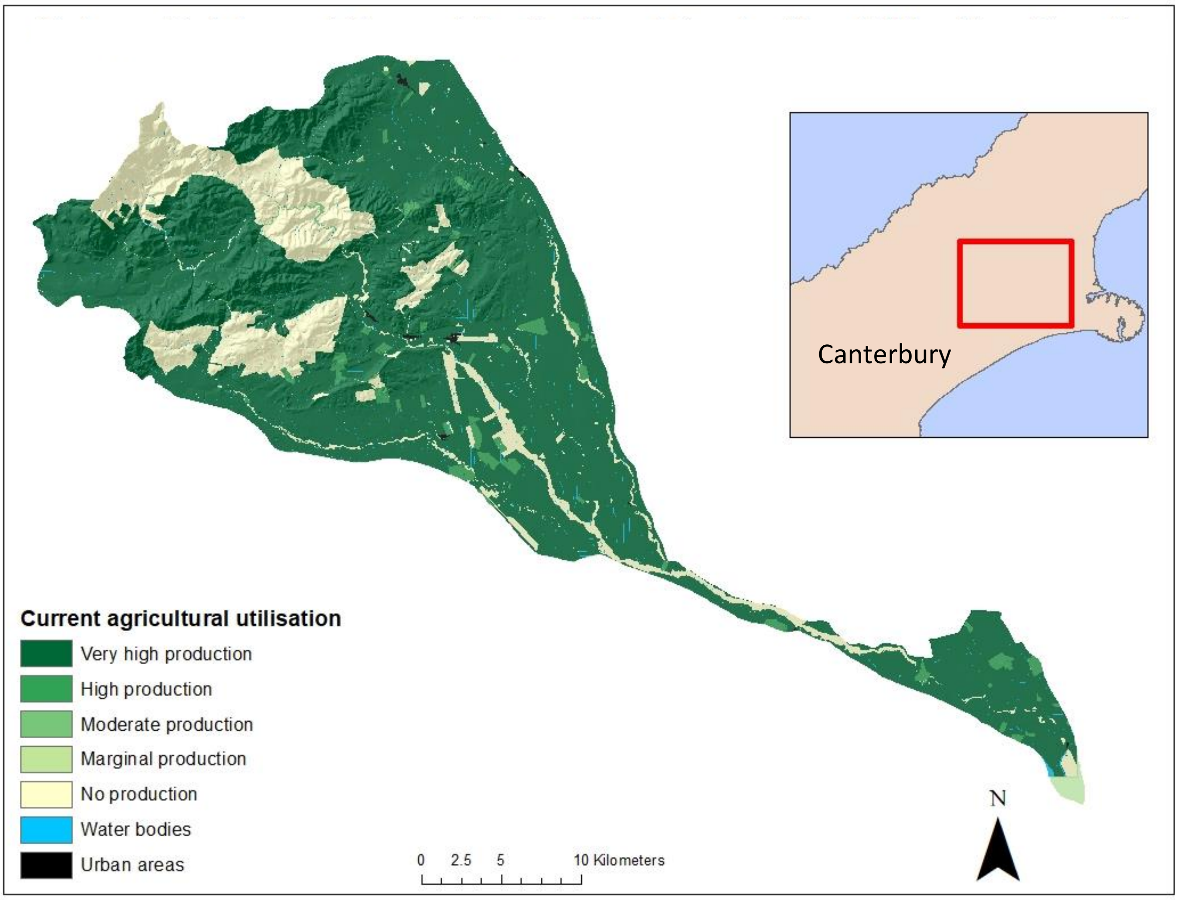

Figure 31. Selwyn catchment current agricultural utilisation.

4.2.3.2 Predicted optimum agricultural productivity

Only Fifty-four square kilometres (7%) of the Selwyn catchment was considered as highly productive. LUCI uses slope, drainage, fertility and aspect of the landscape to determine productivity under this scenario. One hundred and eighty-one square kilometres (24%) was regarded marginal for agricultural productivity. These locations are positioned in the upper catchment at the foothills (Fig. 32).

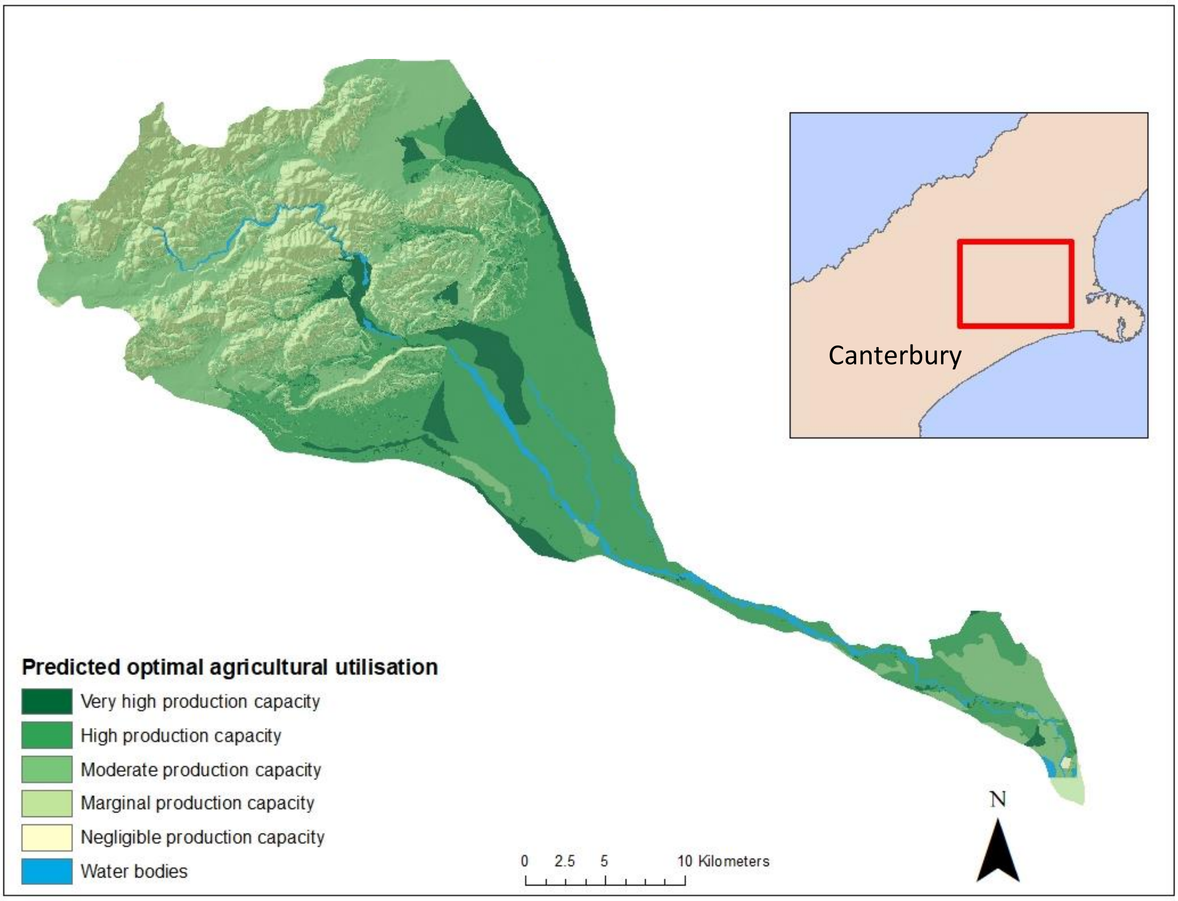

Figure 32. Selwyn catchment predicted optimal agricultural utilisation.

4.2.3.4 Relative agricultural utilisation

The relative agricultural utilisation looks at positions that are over and utilised. Generated results indicate that one hundred and fifty-five square kilometres (15%) of the catchment was significantly over utilised. These positions are mainly located in the upper catchment. Only twenty square kilometres (3%) was regarded as significantly under-utilised. These areas were in the central parts of the catchment on small patches of the land (Fig. 33).

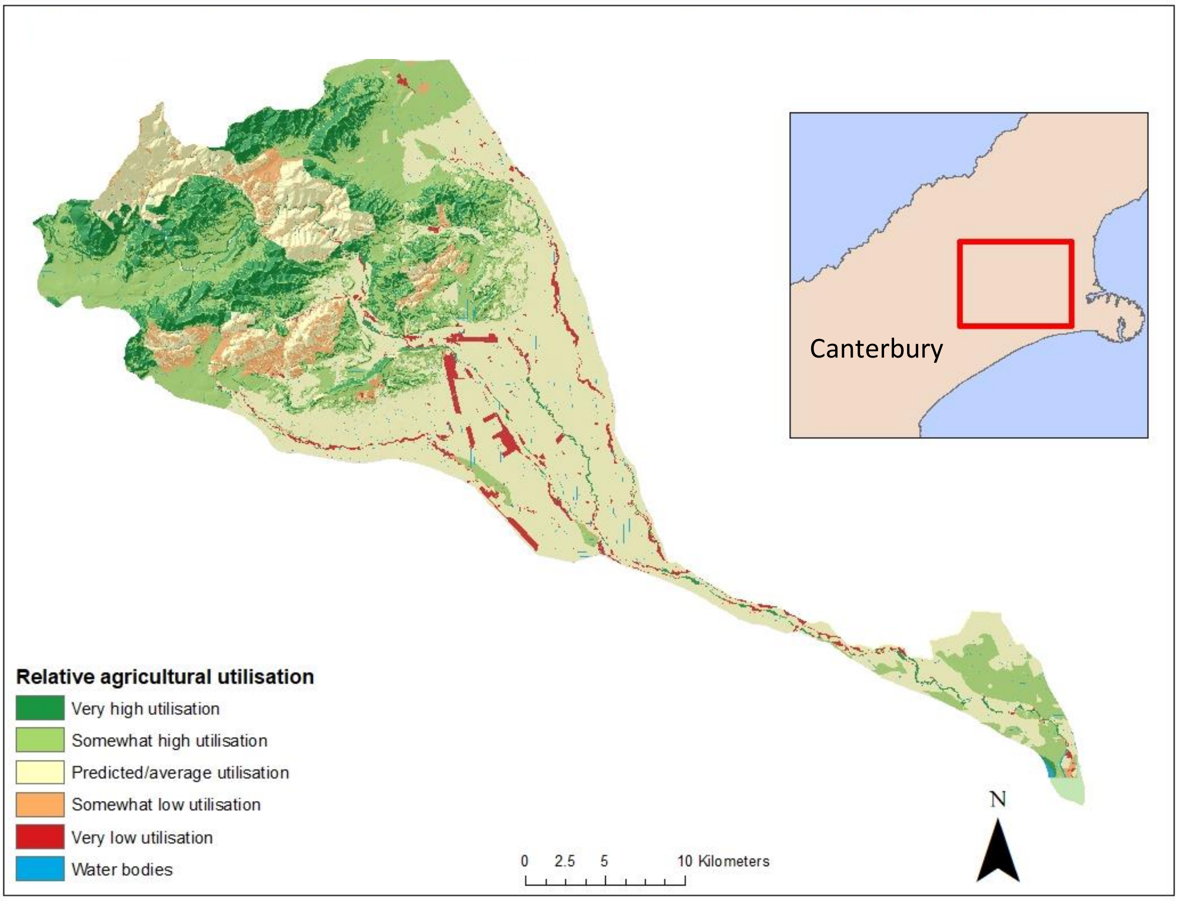

Figure 33. Selwyn catchment relative agricultural utilisation.

4.2.3.5 Agricultural production utilisation

Based on this analysis, sixty square kilometres (8%) of the catchment appeared to be at optimum utilisation and one hundred and thirty-five square kilometres (18%) was regarded as land very unusually utilised (Fig. 35).

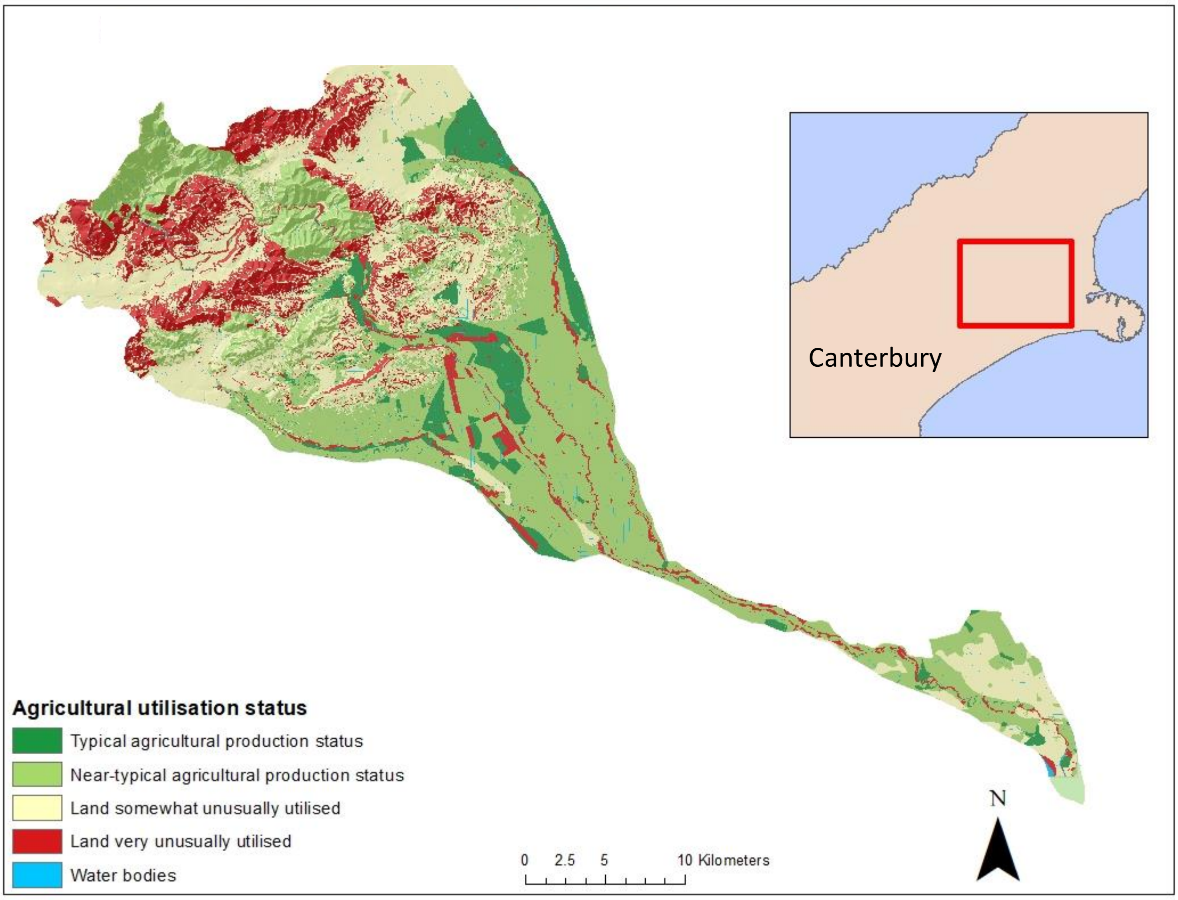

Figure 35. Selwyn catchment agricultural utilisation status.

4.2.4 Trade-offs

4.2.4.1 Agricultual productivity vs nitrogen

The trade-off analysis between agricultural productivity and nitrogen revealed that one and hundred three square kilometres provides an excellent opportunity to improve both agricultural productivity and nitrogen export. There were no positions within the catchment which offer an excellent service provision of both agricultural productivity and nitrogen export (Fig. 35).

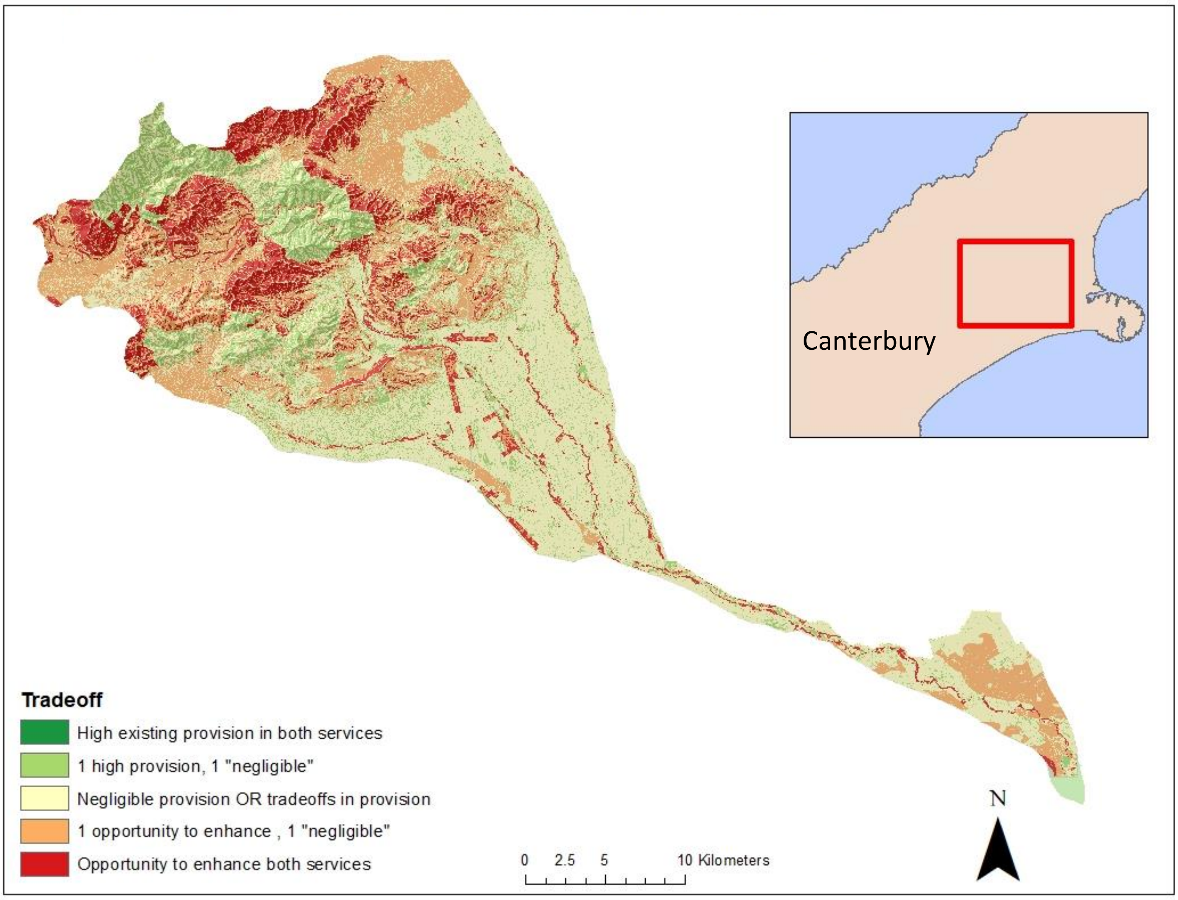

Figure 35. Selwyn catchment agricultural production vs nitrogen trade-off.

4.2.4.2 Agricultual productivity vs phosphorus

Generated results indicated that ninty eight square kilometers (13%) of the Sewlyn catchment provided an excellent opportunity to improve both agricultural productivity and phosphorus export. Again there were no positions within the catchment which offered an excellent service provision of both agricultural productivity and phosphorus export (Fig. 36).

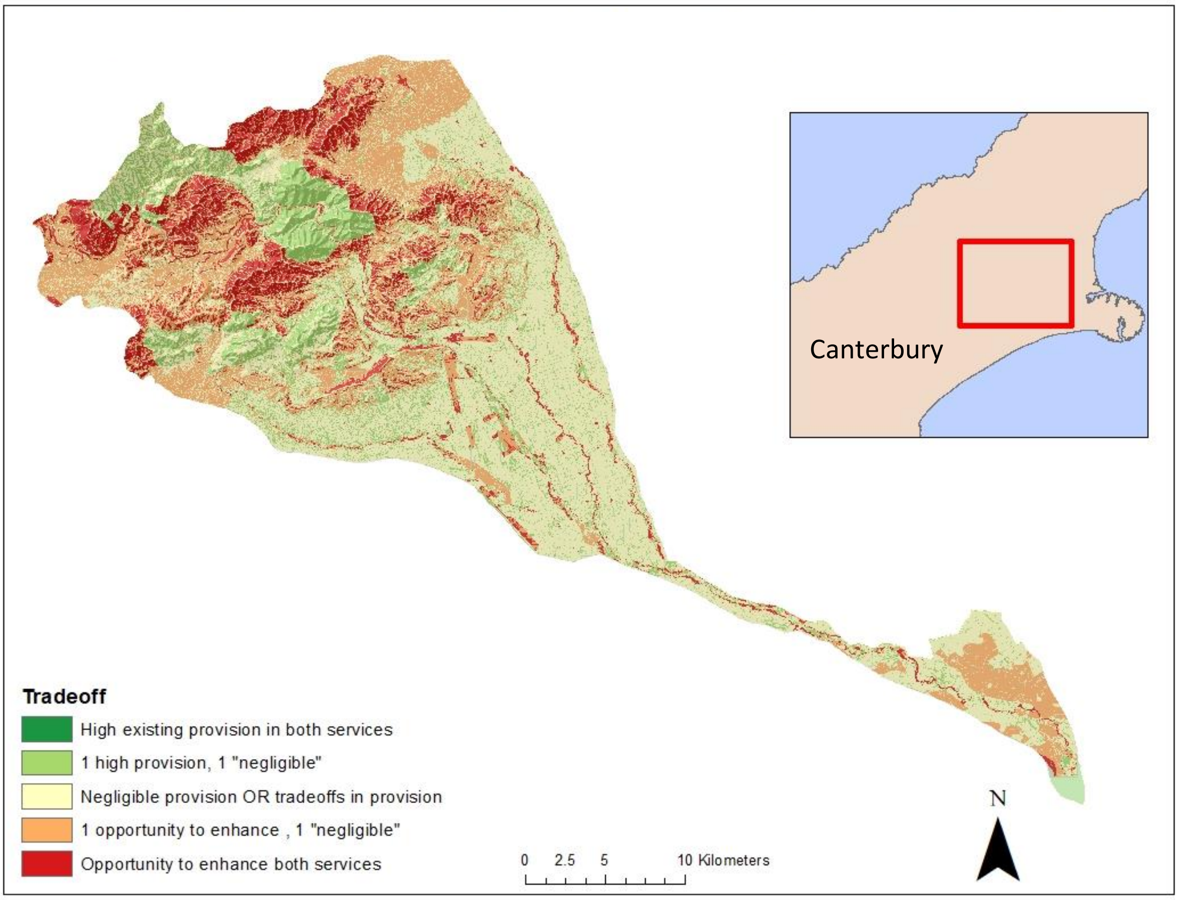

Figure 36. Selwyn catchment agricultural production vs phosphorus trade-off

This chapter has given a detailed description of the outputs generated under scenario one and two to achieve objectives of this research. The next chapter will discuss generated results, give recommendations and conclusions.

CHAPTER 5 DISCUSSION

5.0 Chapter summary

This chapter concludes the thesis. It provides a discussion of the results obtained in chapter 4 and discusses each objective in further detail. Recommendations for future works and a conclusion are given at the end of the chapter.

5.1 Nutrients

The first objective of this study sought to determine sources of nutrients (nitrogen and phosphorus) in the Kaituna and Selwyn catchment.

Based on this analysis, results from using the initial configuration of the model indicated that soils had a major impact on nutrient load in both catchments. These findings matched with those observed in an earlier study by Trodahl M et al. (2016). Given the current state of the Selwyn River catchment and the high number of farms present, this suggests that this configuration of LUCI uses primarily soils to determine nutrient load and does not take into consideration farming activities of an area. Surprisingly, generated nutrient loads for the Kaituna catchment (21 kg/ha/yr.) were similar to those for the Selwyn catchment. These results were not very encouraging considering that the Kaituna catchment is smaller (4,900 ha) and has fewer land use activities compared to the Selwyn catchment (70,000 ha) and has far more agricultural activities. It was expected that nutrient levels in the Selwyn catchment would be higher. Though to some extent soils contribute to the nutrient levels of an area, the impact of land use activities on nutrient levels cannot be eliminated. Furthermore, it is difficult to give recommendations on how to control nutrient loss based solely on soil type.

Subsequently, the model was modified and farm types within the Selwyn catchment were incorporated into LUCI. This modification process allowed LUCI to determine nutrient loads of an area based on land-use activities. Based on this analysis, results indicated that dairy cattle farming was the highest contributor to nutrient loadings within the Selwyn catchment. These results were significant because they corroborated findings of several other studies within the Selwyn catchment which, used different modelling tools to identify sources of pollution in waterways (Cetin, 2014; Hughey & Taylor, 2008).

According to Jenkins, (2017), water quality issues for the Selwyn catchment are driven by land use intensification which has increased nutrient generation from fertiliser application, animal effluent disposal and animal urine patches. The major concern in the catchment is nitrate contamination with groundwater. In the upper reaches the river loses surface water to the groundwater system while in the lower catchment when the groundwater table reaches the elevation of the riverbed, the river gains flow from groundwater. The impact of groundwater contribution in the Selwyn catchment is evident in the significant increase in nutrient levels occurring in rivers recharged by groundwater in the lower reaches.

Efforts to control nutrient leaching in the catchment have been put into practice before and these include use of the Overseer model, which is discussed in detail in the literature review. It is used across New Zealand as a nutrient budget calculator but there are some controversies around the model, such as figures generated for the same farm keep changing as the model is regularly updated (Duncan, 2017), making long term planning difficult. Management interventions in the Selwyn catchment include improved management practices or change to less nitrogen intensive land uses Jenkins, (2017). Whilst changing to less nitrogen intensive land use would be the best solution for the catchment, this would also mean changing from dairy farming to other enterprises such as sheep or beef farming. However, this solution could be difficult to implement due the monetary benefits associated with dairy farming. In relation to groundwater supply, Jenkins (2017) suggests an option of using deeper wells since high nitrate concentrations affect the upper 50-100 m of the aquifer system. This option could work best in areas which use wells but cannot be used in the entire catchment as many areas rely on surface water flows for water supplies.

Despite efforts to improve water quality in the Selwyn catchment, water quality remains an issue of concern. This could be due to the time lag in groundwater transport and escalating land intensification.

Since the generated results indicate LUCI's ability to provide clear guidance for positioning nutrient mitigation solutions. Dairy farmers can use LUCI to better understand how to intercept and retain nutrients before they leach into groundwater and impact water quality.

Various opportunities exist to reduce nutrient export to waterways. Some general strategies include timing and split fertiliser application, riparian planting, and the use of wetlands to filter nutrients. Additionally, to control nutrient sources from dairy cattle farming, the duration controlled grazing system can be used. With this system, cows are given a short period to graze on pasture (four hours) before they are moved to a stand-off facility for excretion and rumination. Animal waste is collected from the stand-off facility, reducing the amount of animal waste that can be transported into waterways (Christensen et al., 2012). Feed pads can also be used and are a similar measure to the duration controlled grazing. They are used to keeping animals off pastures during winter when high rainfall is experienced, reducing the amount of nitrogen lost from urine (Moran & McDonald, 2010). Lastly, fencing around waterways can be done to keep animals off waterways.

Opportunities also exist to mitigate run-off of nutrients from steep slopes particularly in the case of the Kaituna catchment, which has a higher incidence of steeper slopes than the Selwyn. Slope stabilisation strategies that control erosion could be adopted to minimise nutrient export into waterways. These strategies include planting slope-stabilising plants on steep slopes. Plants such as blue carpet, thistles and plantains bind soils making them harder to erode and plant canopies protects the soil surface from raindrop impact erosion (Agassi & Ben-Hur, 1992).

5.2 Agricultural productivity

The second objective of this study was to assess the agricultural utilization status of the study area.

Findings for agricultural productivity under both modelling processes did not show any significant differences. Results for both catchments under the current agricultural productivity indicated that extensive parts of the catchments were highly productive. This analysis is insufficient since it only considers the land cover of an area to determine productivity and does not consider several other important factors such as fertility, drainage, and slope.

However, under the predicted optimal analysis which encompasses drainage, slope, aspect, and fertility factors, a smaller proportion of both catchments was considered highly productive for agricultural purposes. This analysis is very useful to farmers because it identifies positions where agricultural productivity is high and low. This information is important in land use planning.

LUCI further identifies over and underutilised positions within a landscape using the agricultural productivity tool. Under scenario two, 15% of the total catchment was regarded as over utilised whilst only 3% was regarded as underutilised. This can be regarded as a strength for LUCI in comparison to other similar studies such as one by Dharmasiri (2012), which looked at measuring agricultural productivity using the Average Productivity Index (API). Results only indicated the productivity status of the area but did not go further into identifying the over and underutilised positions. Over utilised positions in LUCI refer to areas where there are inefficient or unsuitable agricultural activities whereas underutilised positions indicate positions where there are opportunities to increase agricultural productivity. This information is also very important to both farmers and land planners as it can be used for planning and management purposes.

5.3 Trade-offs

The third objective was to identify the trade-offs between agricultural productivity and water quality.

Generated results for trade-offs between agricultural productivity and water quality (particularly for nitrogen and phosphorus) indicate that there are no positions in either catchment under both modelling scenarios where there is a high provision of both services. In other words, there are no positions where agricultural productivity is accompanied by low nutrient losses. This is so because agriculture was identified as the main contributor of nutrients in waterways hence; it is almost impossible to find locations where agricultural productivity is high with low nutrient losses unless management strategies are in cooperated to control this. Some of these management strategies have been discussed in section 5.1 of this chapter.

Further analysis indicated that there are positions within the landscape where both services could be improved. These positions are in areas where there were average nutrient loads. However, this may be difficult to achieve because as agricultural productivity increases so does the potential for nutrient loss.

According to Inostroza, König, Pickard, and Zhen (2017), trade-offs occur when one ecosystem service is enhanced at the expense of another. In this case, nutrient loss could be enhanced at the expense of reduced agricultural productivity since it is almost impossible to enhance agricultural productivity at the expense of nutrient loss because as agriculture intensifies, nutrient loss increases. A decrease in nutrient loss could be achieved through either changing from dairy to sheep, reducing the number of dairy cattle, or reducing the area under pasture production. This can be difficult to achieve due to the financial benefits associated with dairy farming. However, it may still be possible to reduce production to control nutrient export if the government offers incentives to farmers.

For example, the government can offer tax incentives to dairy farmers in the Selwyn catchment who reduce the number of animals or area under pasture production. Although tax breaks negatively affect the government by lowering its real income, it has a positive impact on farmers through increasing the amount of real income which acts as compensation for loss or reduction in production they would have incurred. In this case, there would also be a positive impact on environmental quality.

Furthermore, the government can create exclusive trading zones for dairy farmers to compensate for a loss of production. These trading zones will ensure ready markets for affected farmers. Although New Zealand has a robust export market for its milk, affected farmers can be given preference in supplying their milk production or can have their milk exported to countries that fetch premium prices.

Lastly, the government can motivate farmers to reduce production through banks. For example, banks such as Rabobank, which serve and support farmers can offer low-interest rate loans to farmers who comply.

5.4 General discussion

Whilst modifying the model, LUCI could not identify new export coefficient values for new farm names. This had an impact on generated results as the total nutrient load value did not change despite adding in new land uses. Positions with farms remained with low nutrient loads. Upon further investigation, it was recognised that this had to do with the LUCI codes, which use land cover multipliers, which are derived from export coefficient values. These land cover multipliers are used to calculate nutrient load in LUCI. This procedure was changed to enable calculations to be done directly from export coefficients and results generated as a result of these changes were more reliable. Furthermore, model developers further adjusted the model so that it uses land cover multipliers and regional averages of stocking, fertiliser application, and irrigation. Initially, land cover multipliers did not include additional information, hence generated results were based on soil type only. This update to the LUCI code allows for a more detailed accounting of these factors on different land cover and not just high producing exotic grassland. In brief, LUCI can now calculate nutrient export using either export coefficients for land cover only or using land cover multipliers and additional information. The input requirements for these two are, however, slightly different. Appendix 4 shows land cover classes with information on stocking, fertiliser, and irrigation.

After modifying the model, no significant differences were shown in the results generated by the agricultural productivity and the trade-off tool. The modification process had major impacts on the water quality outputs only.

5.5 Recommendations

During data collation, specifically for the soil layer, it took time to realise that LUCI is only compatible with the FSL-all attributes layer. Other FSL layers, which did not have the required attributes could not work within LUCI. This is not documented within the LUCI manual and hence it is recommended that the model developers highlight this issue in the manual to avoid confusion to future researchers.

Whilst modifying the model, it was discovered that the AgriBase (2014) layer which contains farm data had polygons that overlapped each other. This had an impact on generated results because two polygons (with different farm names) on the same position had different EC values and in the end, the model could not calculate the nutrient load of that position. It would be recommended that AsureQuality update the polygons and ensure no overlaps occur.

Estimated export coefficient values for some land uses (tourism and enterprises) as stated in the Methods chapter, were used as these were not available in any literature and for the available EC values, ECs from other countries that did not perfectly suit conditions of the Selwyn catchment were used. To achieve better results, it is recommended future research be carried out to develop export coefficients to suit New Zealand conditions.

5.6 Conclusion

This research modified the LUCI model through the inclusion of farm types in the land cover input data file and generated results based on land use. The results of this modification have identified dairy farming as a significant contributor of nutrients in waterways. Although various studies have identified dairy farming as the main contributor of nutrients in the Selwyn catchment, this research has also demonstrated LUCI's ability to provide clear guidance for positioning nutrient mitigation solutions that can assist farmers in meeting freshwater policy requirements. The model results have provided an assessment of the agricultural productivity status of both catchments and identifying positions where there is over and underutilisation of land. This information is essential to farmers and land planners for more effective planning. The trade-off tool managed to identify positions within the Selwyn catchment where trade-offs between agricultural productivity and water quality occur, though interventions to improve water quality are likely to occur at the expense of agricultural productivity.

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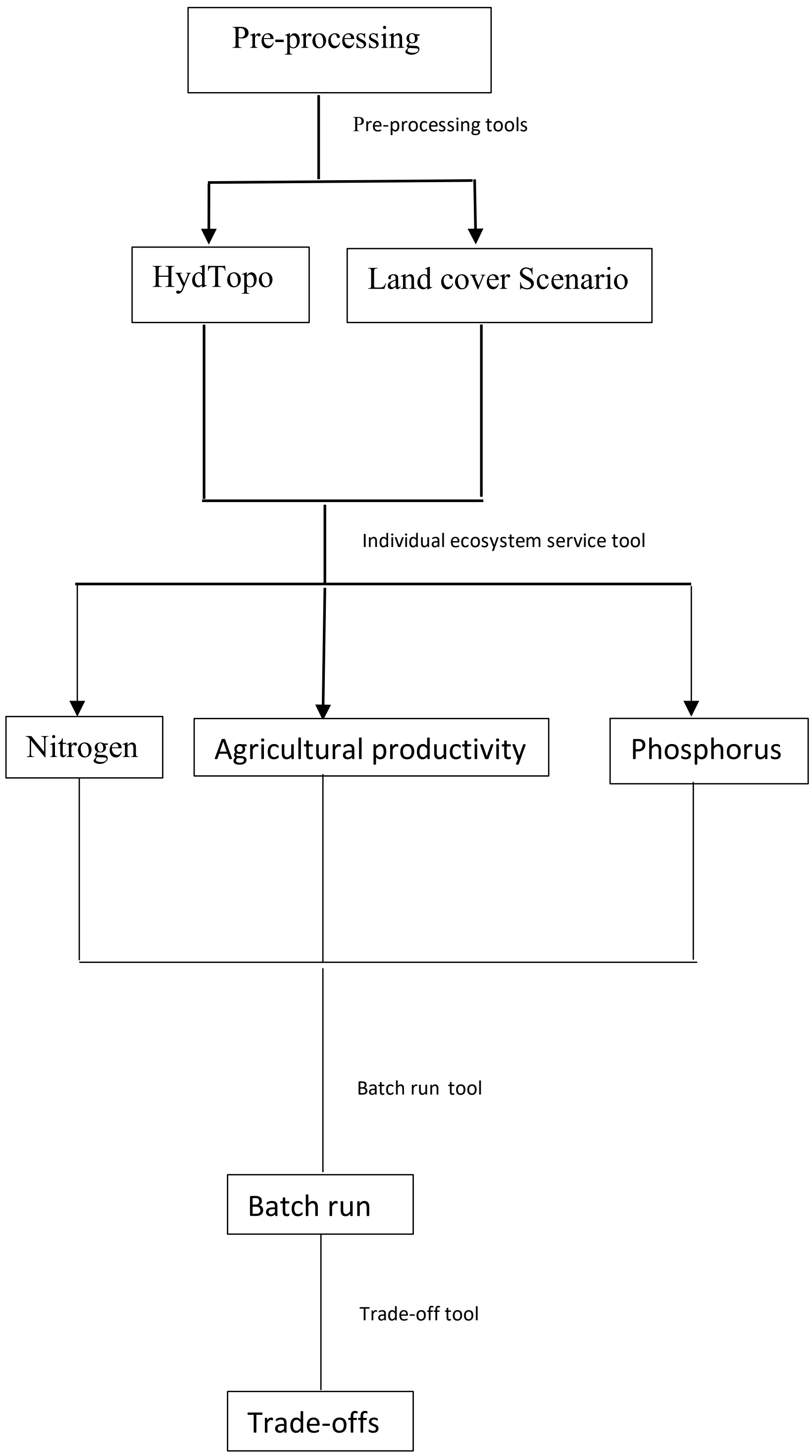
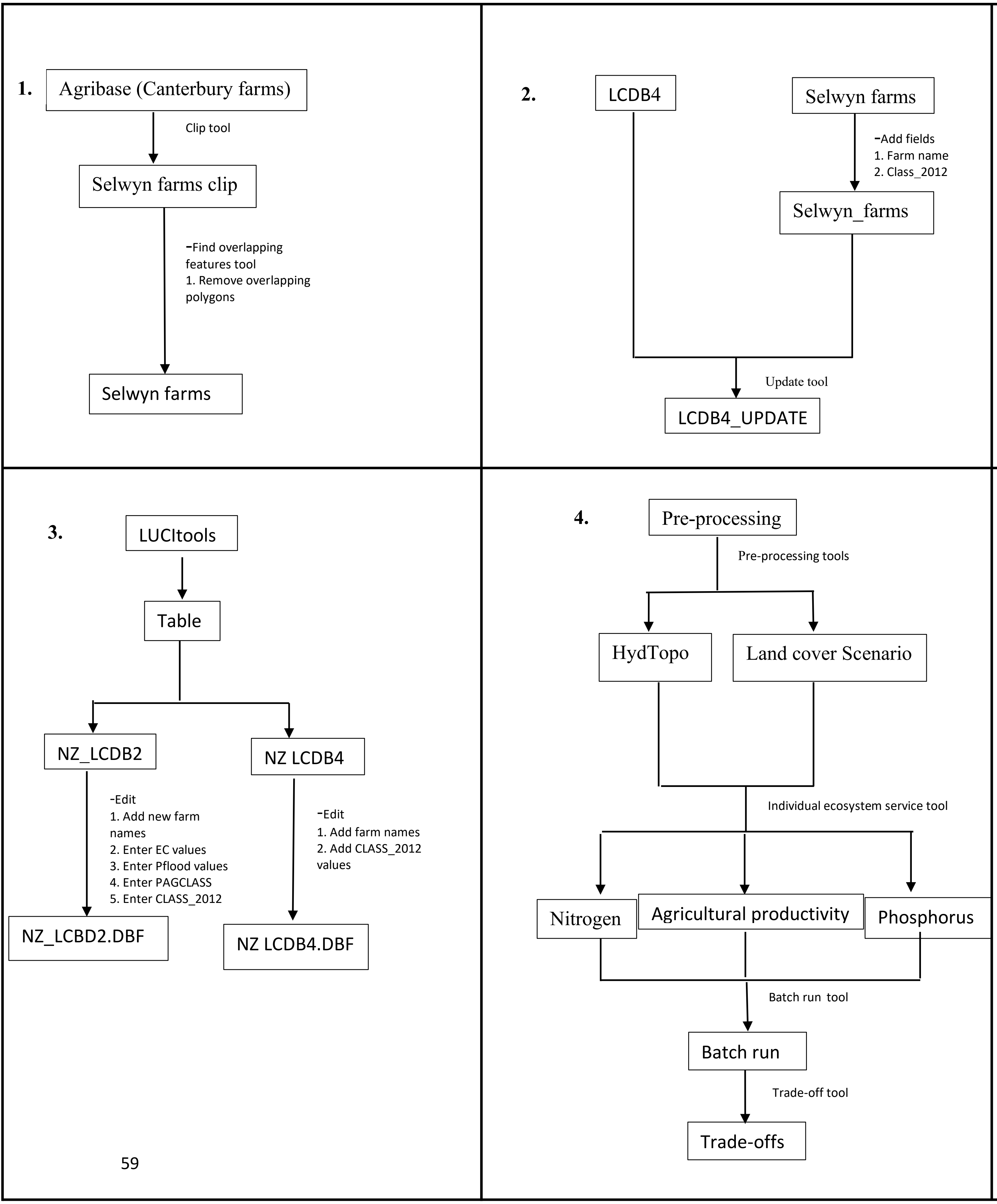
Appendix 1: LUCI Modelling Flow Diagram



Appendix 2: Modification process flow diagram



Appendix 3: Input data for LUCI modification

Farm name	Class_2012	Pflood	PAGCLASS	NEXPCOF	PEXPCOF	Nmult	Pmult
Lifestyle Block	80	1	1	10	1	0.45	0.77
Sheep Farming	81	1	1	9.5	0.94	0.43	0.72
Grazing other people’s stock	82	1	1	9.5	0.94	0.43	0.72
Mixed sheep and Beef Farming	83	1	1	9.5	0.94	0.43	0.72
Beef Cattle Farming	84	1	1	9.5	0.94	0.43	0.72
Deer Farming	85	1	1	9.5	0.94	0.43	0.72
Arable cropping and seed Production	86	1	1	13	0.98	0.59	0.75
Dairy Cattle Farming	87	1	1	37	1.14	1.68	0.88
Pig Farming	88	1	1	10	1	0.45	0.77
Forestry	89	2	5	1.9	0.1	0.09	0.08
Fruit Growing	90	2	1	10	1	0.45	0.77
Horse Farming and Breeding	91	1	2	10	1	0.45	0.77
Enterprises	93	1	1	1.6	0.2	0.07	0.15
Other Livestock	94	1	1	10	1	0.45	0.77
Native Bush	95	1	5	1.6	0.2	0.07	0.15
Goat Farming	96	1	1	10	1	0.45	0.77
Alpaca and Llama Breeding	97	1	2	10	1	0.45	0.77
Poultry Breeding	98	1	2	10	1	0.45	0.77
Tourism	100	1	3	1.6	0.2	0.07	0.15
Vegetable Growing	102	2	1	10	1	0.45	0.77
Other Planted Types	103	2	1	10	1	0.45	0.77
Dairy Dry Stock	104	1	1	27	1.1	1.23	0.85
Nursery Production	105	2	1	10	1	0.45	0.77
Flowers	106	2	1	10	1	0.45	0.77
Dog	107	1	5	1.6	0.2	0.07	0.15
Beekeeping and Hives	108	1	3	1.6	0.2	0.07	0.15

Appendix 4: Land cover data and additional information

Land Cover Name	Include stocking info?	Include fertiliser info?	Include effluent info?	Include irrigation information?
Some LCDB Classes				
Short-rotation Cropland	No	Yes	No	Yes
Vineyard	No	Yes	No	Yes
Orchard and Other Perennial Crops	No	Yes	No	Yes
High Producing Exotic Grassland	Yes	Yes	Yes	Yes
New Land Cover Classes				
High Producing Grassland with Effluent	Yes	No	No	No
Lifestyle Block	Yes	No	No	No
Sheep farming	Yes	No	No	No
Grazing Other Peoples Stock	Yes	No	No	No
Mixed Sheep and Beef Farming	Yes	No	No	No
Beef Cattle Farming	Yes	No	No	No
Deer Farming	Yes	No	No	No
Arable Cropping or Seed Production	No	Yes	No	Yes
Dairy Cattle Farming	Yes	No	No	No
Pig Farming	Yes	No	No	No
Forestry	No	No	No	No
Fruit Growing	No	Yes	No	Yes
Horse Farming and Breeding	Yes	No	No	No
New Record	No	No	No	No
Enterprises	No	No	No	No
Other Livestock	Yes	No	No	No
Native Bush	No	No	No	No
Goat Farming	Yes	No	No	No
Alpaca and/or Llama Breeding	Yes	No	No	No
Poultry Farming	Yes	No	No	No
Unspecified	No	No	No	No
Tourism	No	No	No	No
Vegetable Growing	No	Yes	No	Yes
Other Planted Types	No	Yes	No	Yes
Dairy Dry Stock	Yes	No	No	No